UNIVERSITY OF CALGARY

‘Making’ within Material, Cultural, and Emotional Constraints

by

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ABSTRACT

The Maker Movement aims to democratize technological practices and promises many benefits for people including improved technical literacy, a means for self-expression and agency, and an opportunity to become more than consumers of technology. As part of the Maker Movement, people build hobbyist and utilitarian projects by themselves using programmable electronics (e.g., microcontroller, sensors, actuators) and software tools. While the Maker Movement is gaining momentum globally, some people are left out. Constraints such as material limitations, educational culture restrictions, and emotional or behavioral difficulties can often limit people from taking part in the Maker Movement. We refer to the systematic investigation of how diverse people respond to making-centered activities within constraints as an *exploration of making within constraints*.

In this dissertation, we (1) study how people respond to creating physical objects by themselves within constraints and, (2) investigate how to design technology that can help makers within constraints. We conducted an observational study in an impoverished school in India and identified the students' challenges and their strategies for making within material and educational culture constraints. We conducted a second study with at-promise youth in Canada and identified a set of lessons learned to engage youth within emotional and behavioral constraints in making-centered activities. Leveraging our observations, we proposed Augmented Reality (AR)-mediated prototyping as a way to address material constraints. AR-mediated prototyping can help makers to build, program, interact with and iterate on physical computing projects that combine

both real-world and stand-in virtual electronic components. We designed, implemented, and evaluated a technology probe, Polymorphic Cube (PMC), as an instance of our vision. Our results show that PMC helped participants prototype despite missing I/O electronic components, and highlighted how AR-mediated prototyping extends to exploring project ideas, tinkering with implementation, and making with others.

Informed by our empirical and design explorations, we suggest a set of characteristics of constraints and implications for designing future technologies for makers within constraints. In the long-term, we hope that this research will inspire interaction designers to develop new tools that can help resolve constraints for making.

PUBLICATIONS

Some ideas and figures in this dissertation have appeared previously in the following publications:

Sowmya Somanath, Lora Oehlberg, Janette Hughes, Ehud Sharlin, and Mario Costa Sousa. 'Maker' within Constraints: Exploratory Study of Young Learners using Arduino at a High School in India. In *Proceedings of the CHI'17: International Conference on Human Factors in Computing*, pages 96-108. ACM, 2017.

Sowmya Somanath, Lora Oehlberg, and Ehud Sharlin. Making despite Material Constraints within Augmented Reality-mediated Prototyping. University of Calgary PRISM Technical Report, http://hdl.handle.net/1880/52219, 2017.

Sowmya Somanath, Laura Morrison, Janette Hughes, Ehud Sharlin, and Mario Costa Sousa. Engaging 'At-Risk' Students through Maker Culture Activities. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 150–158. ACM, 2016.

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"Families are the compass that guides us. They are the inspiration to reach great heights, and our comfort when we occasionally falter. "

To my parents, Lakshmi and Somanath,

Thank you for being such supportive parents.

To my sister, Gowri,

Thank you for showing me that we can dream big.

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INTRODUCTION

The vision of the Maker Movement is to democratize technological practices and empower people to become producers of artifacts and knowledge (Tanenbaum et al., 2013). As part of the Maker Movement, people build physical computing projects such as toys, robots, and utilitarian products by themselves using art and craft materials, programmable electronics (e.g., microcontrollers, sensors, and actuators), software, and fabrication tools. While the Maker Movement is gaining momentum all over the world, some people are left behind. Factors that stem from social problems, such as resource limitations, cultural restrictions, and emotional or behavioral difficulties of people, act as constraints for taking part in the Maker Movement (e.g., Buechley et al., 2009; Vossoughi et al., 2013; Bean and Rosner, 2014). In this dissertation, we conduct a systematic investigation of how people respond to making-centered activities within constraints, and refer to this as an *exploration of making within constraints*.

The main objective of this dissertation research is to explore *making within constraints*. This includes: (1) expanding our understanding of how people respond to creating physical objects by themselves within constraints, and, (2) investigating how to design technology that can address making within constraints.

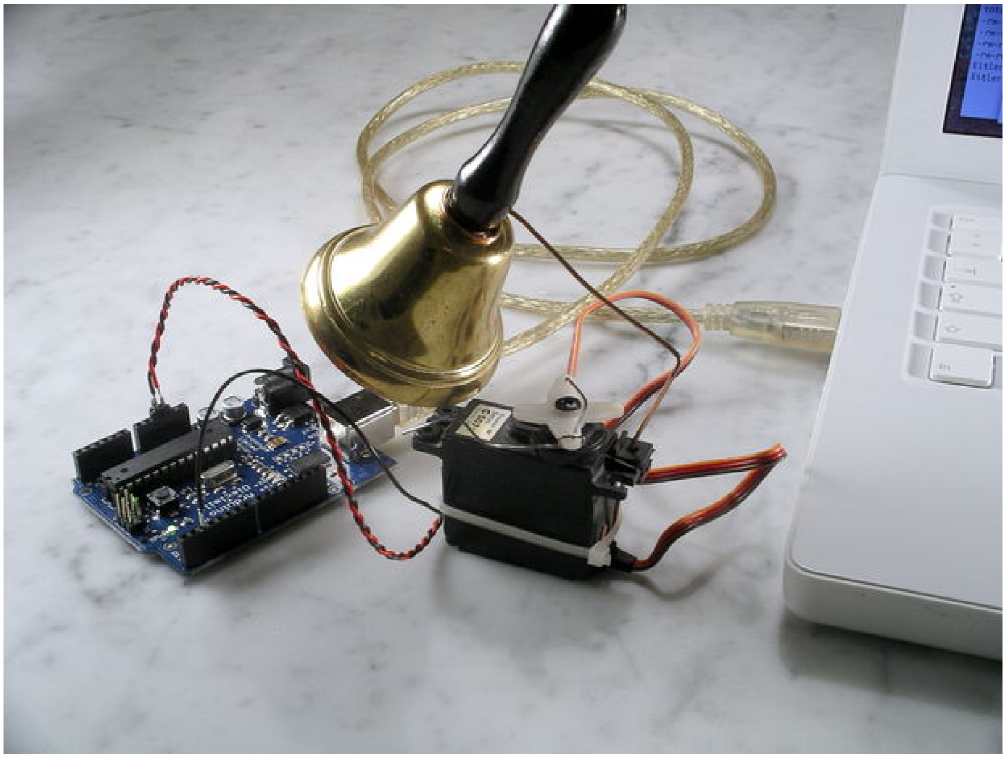


Figure 1: Arduino controlled bell counter[1].

This chapter begins by first discussing the motivation for this dissertation research. Second, we outline the scope of the research undertaken. Third, we list the research goals that this dissertation explores. Fourth, we provide a brief discussion of the methodological approach to the research. Fifth, we list the main contributions of this research. Last, we provide an outline of the different chapters of this dissertation.

1.1 MOTIVATION

The term Maker Movement refers broadly to a growing number of people who are engaged in the creative production of artifacts in their daily lives (Figure 1) using a range

1 Source: http://www.instructables.com/id/Arduino-XMAS-hitcounter/

of hardware (e.g., Arduino, MaKey MaKey, littleBits) and software technologies, and Internet-shared plans (Burke, 2014; Halverson and Sheridan, 2014). The Maker Movement is often celebrated as a movement with democratic attributes. It emphasizes that everyone can create with technology (Dougherty, 2013; Roedl et al., 2015). There are three reasons the movement is said to be democratic. First, the pleasure of making is basic and human, which makes it widely appealing and empowering. Researchers have learned that creating something with one's own hands, rather than purchasing a mass-produced object, is often described as a pleasurable experience (e.g., Crawford, 2010; Buechley and Perner-Wilson, 2012; Tanenbaum et al., 2013). For example, a small case study of an online steampunk community has shown that making may give rise to feelings of self-sufficiency and empowerment (Akah and Bardzell, 2010).

Second, makers share knowledge and resources widely in an open-source manner. Silver (2009) describes knowledge sharing as an explicit ethos of Maker Culture – makers believe in open-source, no ownership, and that ideas are free. The development of physical and online communities, called *makerspaces*, have created opportunities for people to practice and share their making experiences (Burke, 2014). Kuznetsov and Paulos (2010), in their survey of over 2600 individuals across a range of online DIY communities, found that makers are motivated to share for several reasons: receiving feedback on projects, educating others, and showcasing personal ideas and skills. This way making is often viewed as a viable means for increasing technology literacy in society.

Third, makers actively resist or critique consumer culture. For example, Rosner and Bean (2009) describe how IKEA hackers creatively repurpose IKEA products to create personalized objects. On one hand, IKEA hackers describe the standardization of IKEA parts as foundational to sharing of hacks. On the other hand, they often critique the generic style. Such instances of maker practices represent paradoxical relationships to mass culture and actively question the values associated with technology design. This way making is often is viewed as a means for building personalized products and self-expression.

Motivated by these benefits and because of the availability of low-cost programmable tools (such as programmable electronics, 3D printers, embroidery machines etc.) people can buy and use in homes, offices, and studios to create finished product-like artifacts, the Maker Movement has spread to schools, museums, libraries, and dedicated studios (Martin, 2015).

However, despite this growing global trend, some people do not have opportunities to enjoy the benefits of the Maker Movement (Buechley et al., 2009; Ames et al., 2014; Barton et al., 2016). Factors that stem from real-world problems severely restrict the extent to which people can take part in the Maker Movement (e.g., Vossoughi et al., 2013; Bean and Rosner, 2014; Taylor et al., 2016; Meissner et al., 2017). For instance, people need material resources to build a physical object. However, not everyone has easy or immediate access to the resources such as electronics and fabrication tools for making (e.g., Sipitakiat et al., 2004; Bean and Rosner, 2014). Similarly, makers' projects are often invested with passion and emotion (Davies, 2017, ch. 8). However, emotional or behavioral problems such as low self-esteem, low frustration threshold, and a general lack of motivation in learning activities can make it difficult for people to take part in making-centered activities (e.g., Kuznetsov et al., 2011; Lin and Shaer, 2016).

Within this space, we see an opportunity to engage Human-Computer Interaction (HCI) research for understanding how people respond to making within constraints and developing tools that can be valuable to makers within constraints. In the next section, we discuss three types of constraints that can inhibit the Maker Movement from taking hold.

1.1.1 *Types of Constraints*

In this dissertation, we look at three types of constraints to making: (1) lack of material resources, (2) traditional education culture restrictions, and (3) emotional or behavioral difficulties. The term 'constraints' here refers to factors that limit people from taking part in making-centered activities using programmable electronics. Our list of constraints is not exhaustive. Previous research has explored other types of constraints such as person impairment (e.g., Meissner et al., 2017). However, as a starting point and thanks to opportunity, we look to explore how people create physical objects by themselves despite material, cultural, and emotional or behavioral constraints.

- **Material Constraints** – This constraint is potentially a large reason for people to stop engaging in any kind of technological practices, including making (e.g., Sipitakiat et al., 2004). In this dissertation, we explore how limited or no access to computational materials such as electronics affect making.

- **Educational Culture Constraints** – Maker Education is a fast growing subset of the Maker Movement (Dougherty, 2012; Halverson and Sheridan, 2014). As part of Maker Education, making-centered activities are introduced to students in schools and after-school programs. However, education systems, which focus on content delivery and quantitative assessment, are often in conflict with a do-it-yourself (DIY) approach to problem solving. Such education systems often limit direct hands-on experiences and thus, influence the type of activity in which students get involved (Resnick and Rosenbaum, 2013). In this dissertation, we explore "textbook culture" (Kumar, 1988) as an educational culture that constrains making.

- **Emotional or Behavioural Constraints** – A smaller population of people who are exposed to making-centered activities have emotional or behavioral constraints (e.g., Kuznetsov et al., 2011; Stager, 2013). These constraints stem from adverse factors such as family problems, substance use, or trauma. They prevent children and youth from successfully transitioning to adulthood and achieving economic self-sufficiency (Kaufman and Bradbury, 1992; McMillan and Reed, 1994). In this dissertation, we explore how problems such as lack of motivation for learning activities, low frustration threshold, and limited so-called soft skills (i.e. collaboration, choice making, self-determination) affect making.

1.2 RESEARCH GOALS

The overarching goal of this dissertation research is to further our understanding of *making within constraints*. This overarching goal is composed of two sub-goals:

Goal 1. Understand how people respond to making within material, cultural, and emotional or behavioral constraints.

To inform future researchers and interaction designers interested in broadening participation in the Maker Movement, it is important to observe maker practices in non traditional settings with diverse audiences.

Goal 2. Investigate how technology can help making within constraints.

HCI researchers have suggested that new software and hardware tools can assist in promoting maker practices (Buechley et al., 2008; Tanenbaum et al., 2013). Based on our insights about current maker practices within constraints, we can design and develop tools that address making within constraints.

1.3 RESEARCH SCOPE AND AUDIENCE

Our research into *making within constraints* is primarily influenced by past studies in the areas of HCI and Education. For tool development, we primarily draw from research in HCI.

HCI researches the use of computers by people and the design of systems that are useful, usable, and enjoyable for the people who use them. It is a multidisciplinary field and is inclusive of ideas and contributions from other fields such as computer science, engineering, education, design, social, cognitive and psychological sciences, and more. Taking an HCI approach to research underpins our view that understanding more about people can help us create better tools for a diversity of people.

The primary audiences for the work presented in this dissertation are HCI researchers and interaction designers. We hope that the exploration of *making within constraints*, including the observational studies and design exploration, inspire and inform the design process of developing a new class of tools for makers within constraints.

1.4 RESEARCH METHODOLOGY

In this research, we want to expand our understanding of *making within constraints* and, informed by our insights, build tools for makers. As such, the research is highly exploratory in nature. The overarching methodology is to use qualitative observation to deepen our understanding of making within constraints, and then to leverage this understanding to design new approaches to making.

1.4.1 *Qualitative Observation*

We use qualitative research to expand our understanding of making within constraints (Chapters 3 & 4). The reason for conducting qualitative research is that we seek to explore an experience (making within constraints), rather than confirm a hypothesis (Creswell and Poth, 2017). Qualitative research is "deemed to be much more fluid and flexible than quantitative research in that it emphasizes discovering novel or unanticipated findings and the possibility of altering research plans in response to such serendipitous occurrence" (Bryman, 1984, p.5).

The core method used in this research is qualitative observation (Denzin and Lincoln, 2011). In this method, a rich set of data is gathered, then analyzed in an exploratory way to form some new understanding of the data and how it relates to the world. There are several methods available for qualitative data analysis. We use the constructivist approach to grounded theory method. This approach "explicitly assumes that any theoretical rendering offers an interpretive portrayal of the studied world, not an exact picture of it" (Charmaz, 2014, p.17). While the data sources and exact process of data analysis varied in our research (explained in detail in individual chapters), the overarching approach was similar to the grounded theory coding method: (1) an initial phase involving carefully labelling data, followed by (2) a focused phase that uses the initial codes to sort, synthesize, integrate, and organize large amounts of data (Charmaz, 2014, ch. 5).

Qualitative findings are descriptive and interpretive. Fossey et al. (2002) argues that evaluating qualitative findings is related to their trustworthiness, which in turn is related to presentation. To increase trustworthiness, we strive to do the following: (1) use quotations (i.e. participants' own words) juxtaposed with our description and interpretation (to show authenticity), and (2) we provide sufficiently detailed descriptions to show the linkages between the findings and the data from which they are derived.

1.4.2 *Building Technology*

HCI is a design-oriented field (Fallman, 2003). Design here refers to creating research prototypes based, for example, on theories, fieldwork, or novel and innovative ideas. Fallman (2003) argues that such prototypes are often borne out of necessity, so that researchers are able to setup experiments for testing and evaluating their ideas. The intent of the research prototype is to produce knowledge for the research communities, and not to make a commercially viable product.

We use the research through design method (Zimmerman et al., 2007) to build our research prototype (Chapter 5). In this method, researchers are grounded in empirical or theoretical knowledge by performing the upfront research. Per this method, researchers take an active process of ideating, iterating, and critiquing possible solutions until they arrive at a possible right solution. The final output of the activity is a concrete problem framing and a series of artifacts – models, prototypes, and documentation of the design process.

1.5 RESEARCH CONTRIBUTIONS

This dissertation makes six contributions to the study of *making within constraints*.

1. We contribute findings from a study that examines making within material and educational culture constraints (Chapter 3).
2. We contribute findings from a study that examines making within emotional or behavioral constraints (Chapter 4).
3. Informed by our studies, we contribute lessons learned that can serve as suggestions for future researchers conducting maker workshops within constraints (Chapters 3 & 4).
4. We propose a vision for developing *Augmented Reality (AR)-mediated prototyping* tools that can help makers continue to build physical projects despite material constraints. AR-mediated prototyping tools allow makers to blend virtual and real-world prototyping materials to address a lack of materials (Chapter 5).
5. We contribute the design, implementation, and evaluation of a technology probe, *Polymorphic Cube (PMC)*, based on our vision of AR-mediated prototyping. PMC allows makers to continue to build physical circuits despite missing input/output (I/O) electronic components (Chapter 5).
6. Informed by the empirical and design explorations, we contribute a set of characteristics of constraints for making and implications for technology design (Chapter 6).

1.6 DISSERTATION OUTLINE

The remainder of this dissertation is organized as follows: in Chapter 2, we discuss the background and related literature relevant to our study of *making within constraints*. Chapter 3 discusses an observational study of how students in an impoverished school in India react to making-centered activities within material and educational culture constraints. Chapter 4 discusses an observational study of engaging youth within emotional or behavioral constraints in making-centered activities. In Chapter 5, we first introduce our vision for developing AR-mediated prototyping tools. Based on vision we discuss design, implementation, and evaluation of a maker tool we developed, Polymorphic Cube. Informed by our empirical and design explorations in Chapter 6, we discuss the characteristics of constraints for making and present a set of considerations for designing future tools for makers within constraints. Lastly, in Chapter 7 we revisit the goals and contributions of this dissertation and conclude with directions for future work.

2

BACKGROUND AND RELATED WORK

In this chapter, we discuss background and related work relevant to this entire dissertation. We begin by discussing three research areas that advocate for hands-on experiences (Education, Tangible User Interfaces, and Physical Computing). We then provide a focused discussion of the Maker Movement. After the theoretical discussion, we provide a snapshot of the technologies available for making. Lastly, we discuss instances of research that describe maker practices within constraints. To clarify the differences and similarities between our work and existing literature, we revisit research projects discussed here in the following chapters of this dissertation.

2.1 THEORETICAL CONCEPTS

Making things by oneself is not a new idea. Numerous researchers in science, technology, engineering, arts, and mathematics (STEAM) fields have studied and advocated for hands-on experiences (e.g., Pestalozzi, 1907; Papert and Harel, 1991; Ishii and Ullmer, 1997; Dewey, 1998). In this section, we present a snapshot of the research and ideas, which we think best frames the concepts related to hands-on experiences and the Maker Movement.

Figure 2: Froebel Kindergarten (Brosterman et al., 1997)[1]and Froebel Gifts (Brosterman et al., 1997)[2].

2.1.1 *Learning by Doing*

Several theories in the past (~1700–1900) have advocated for open-ended, hands-on, and personal learning approaches. Pestalozzi (1977) in his progressive pedagogy favored hands-on activities and direct concrete observations. He argued that since children learn through active physical education the use of “tools of perception" (e.g. apples, stones etc.) in daily coursework would help develop distinct ideas.

Building upon the idea of “tools of perception” Brosterman et al. (1997), designed physical educational tools, “occupation material” or Froebel “gifts”, to teach students concepts such as spatial relationships, shape, gravity, and rearranging and reassembling (Figure 2). Montessori embraced these principles and placed emphasis on freedom in learning, notably on free use of materials for learning specific concepts (Montessori, 1946; Lillard, 1972; Montessori, 2013).

1 Source: `https://goo.gl/ksC0Y4content`
2 Source: `https://goo.gl/CLrJkO`

Around the same time, Dewey (1998) influenced by progressive pedagogy principles proposed that learning is a social and interactive process, arguing that children should be allowed to interact with the curriculum, providing them with an opportunity to learn not only what is pre-determined but also to be able to explore and actively build knowledge about the topic of study.

Piaget further advanced these theories by proposing Constructivism wherein he argued that knowledge is constructed by experience and that every child or adolescent "require that every new truth to be learned be rediscovered or at least reconstructed by the student, and not simply imparted to him" (Piaget, 1973, p. 15).

Constructionism, proposed by Papert and Harel (1991), combines the Piagetian framing of the learner as knowledge-builder with Deweyan processes of learning through hands-on, experiential (Kolb et al., 2001), and inquiry-based activities (Alesandrini and Larson, 2002). Papert proposed that although learning happens in the learner's head, it is more reliable, real and shareable when the learner is engaged in a personally meaningful activity of making tangible objects.

2.1.2 *Tangible User Interfaces*

Tangible user interfaces (TUI), are a type of interface where people can interact with digital information through a physical environment (Fitzmaurice et al., 1995; Fitzmaurice, 1996; Ishii and Ullmer, 1997). They can be considered the contemporary "tools of perception". TUIs consist of tangible (physical objects) and intangible (graphics and audio) representations. People directly grasp and manipulate the tangible representations to physically explore digital information. The intangible representations complement the tangible representations (Figure 3). For example, Illuminating Clay (Figure 4) is a TUI for

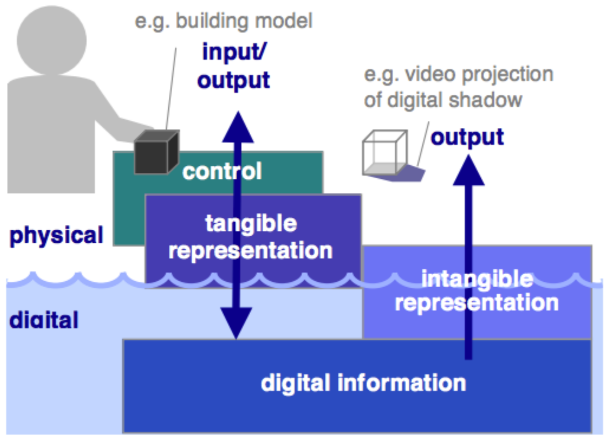


Figure 3: TUI model (Ishii, 2008). A physical (tangible) interface represents digital information. The interface consists of a physical control object that is graspable and enables in input/output interaction. Intangible representation (e.g. video projection) may complement tangible representation by synchronizing with it.

exploring topography of a landscape model. It consists of both tangible representation – a physical clay model, and intangible representation - projection, and visual interface for analysing landscape models (Piper et al., 2002).

Researchers have argued that TUIs are a “natural" form of interaction and lower the threshold for interaction; because we know how to interact with physical objects, it becomes easy to engage with them (Ishii and Ullmer, 1997; Zuckerman et al., 2005; Ishii, 2008).

2.1.3 *Physical Computing*

Physical computing places the power to build a physical interactive system in the hands of an individual. Physical computing projects use both software and hardware that can sense and respond to the real-world. The main emphasis in physical computing is about

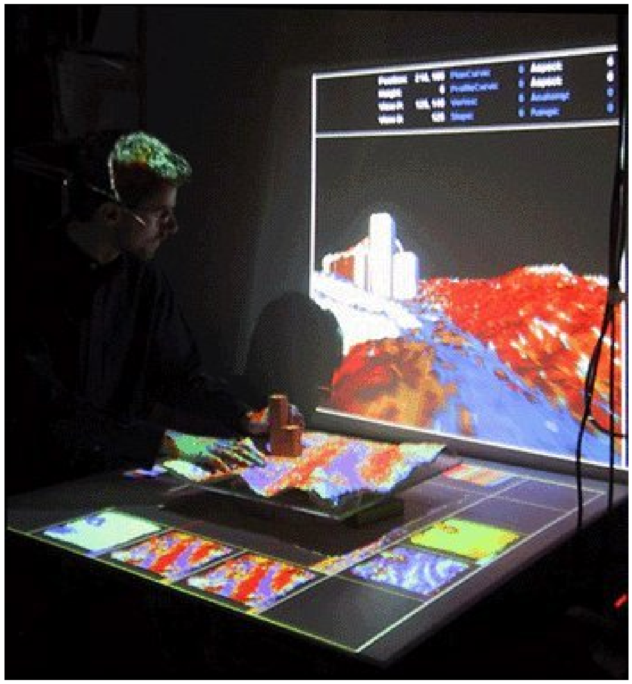


Figure 4: Example of a Tangible User Interface: Illuminating Clay (Piper et al., 2002).

creating a conversation between the physical world and the virtual world of the computer (O'Sullivan and Igoe, 2004). Figure 5 shows the different parts of a physical computing project.

1. Transduction – is the core principle of physical computing. It is the conversion of one form of energy into another. For example, converting various forms of energy, such as light, heat, or pressure, into the electronic energy that a computer can understand is transduction.

2. Input – is the ability to express oneself on a computer. For example, input transducers, such as switches convert light into electrical energy.

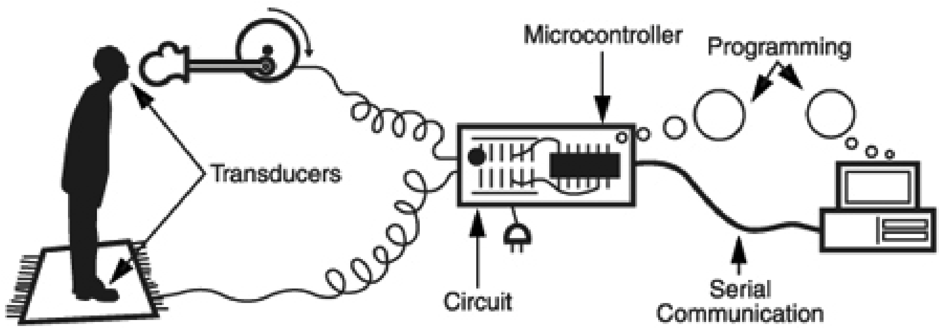


Figure 5: The parts of a physical computing project (O'Sullivan and Igoe, 2004).

3. Output – is the ability of a device to change the world. For example, output transducers, such as motors and buzzers, convert electrical energy into the various forms of energy that the body can sense.

4. Electronic Circuit – is composed of individual electronic components connected by conductive wires or traces through which electric current can flow. Circuits usually described in a diagram called schematic, shows how the individual components are connected to each other.

5. Microcontroller – is a small and simple computer that can receive information from sensors, control basic motors and other devices that create physical change, and send information to computers and other devices.

6. Processing – is the ability of a computer to read the input, make decisions based on the changes it reads, and activate outputs or send messages to other computers. Processing involves programming.

7. Digital and Analog – when only two states are considered for processing, it is called digital. Alternatively, when a continuous range of multiple states is considered, it

is called analog. For example, a digital output can turn a light on or off; an analog output can make the light brighter or dimmer.

8. Serial and Parallel – events that happen one at a time are called serial events. When several events happen simultaneously, they are called parallel events.

O'Sullivan and Igoe (2004) posit that building physical computing projects will allow people to create new types of systems. Physical computing projects can sense more of the human body, and create applications for the physical world (e.g., applications that open a door, or start a car).

2.1.4 *Maker Movement*

The foundations of the Maker Movement are built on many of the past explorations discussed above. Some of the proposed benefits of the Maker Movement are the same as those suggested by the hands-on learning theories and TUIs: leverage our familiarity with the real world, help develop agency, and improved learning (e.g., Dougherty, 2013; Martin, 2015). Moreover, physical computing projects are a type of making-centered activity introduced as part of many do-it-yourself (DIY) workshops (Peppler et al., 2016). In this section, we discuss the Maker Movement and related terminologies such as maker, making, and maker mindset.

2.1.4.1 *Maker*

With the introduction of DIY approach to interaction with technology, the role of human in Human-Computer Interaction (HCI) has expanded. Originally, the discipline of HCI was focused on the design and use of computer technology (Card et al., 1983) and the main goal was to improve the *interaction* (e.g. tool use, input/output communication, experience) between the human and the computer (Hornbaek and Oulasvirta, 2017). Within this framing, the rhetoric for the human in HCI was "user". The role of the human was to "use" technology. The person was considered a "fragile beast under threat from technology and a duty for HCI researchers [was] to help rescue them" (Cooper and Bowers, 1995, p.8).

However, over the last decade, researchers have sought to expand the role and abilities of the human in HCI. Numerous researchers have argued that people can not only "use" technology, but instead can build, modify, maintain, repair, and re-purpose technology (e.g., Buechley et al., 2009; Kuznetsov and Paulos, 2010; Mota, 2011; Tanenbaum et al., 2013). Based on this conception of the human in HCI, the rhetoric has expanded to include the terms "maker", "crafter", "hacker", and "tinkerer" (Roedl et al., 2015, p.5).

Roedl et al. (2015) describe makers as "materially empowered subjects" (p. 6) – maker as a subject is empowered by the skills and abilities embodied in her material relationship to technology. Makers view "finished products" as "unfinished". They are able to modify technology to suit their purposes for pragmatic purposes and/or as a creative statement of self-expression. Makers also repair and repurpose "consumer waste". Because makers do not view technology as finished products, they engage in modifying the technology beyond the limits of its design. For example, Kim and Paulos (2011) analyzed examples from DIY enthusiasts who adapt and reuse electronic waste and post their results online. Lastly, makers want to create more personal, satisfying, and sustainable relationship with the material objects. For example, Rosner and Bean (2009) observe that satisfaction gained through personalization is an important motivation for IKEA hackers.

Based on the above description, in the broadest sense, maker is a person who wants to create things for a variety of reasons: statement of self-expression, for sustainability reasons, or for personal satisfaction (Roedl et al., 2015). **In this dissertation, we use the term maker to refer to the capacity of any person to build open-ended physical computing projects using programmable electronics (e.g., Arduino [3], MaKey MaKey [4])**.

2.1.4.2 *Maker Mindset*

Narratives of the Maker Movement, often describe maker as a subject possessing certain qualities or attributes. Dale Dougherty formalized this concept and introduced the term "maker mindset" (Honey and Kanter, 2013, ch.1). The maker mindset is based on a type of mindset called the "growth mindset", a term discussed by Dweck (2006). People with growth mindset tend to believe that capabilities can be developed, improved, and expanded. They are tolerant to risk and failure. Martin (2015) builds on Dougherty (2013) and presented a more specific list of what the maker mindset includes:

Playful – Martin (2015) suggests that playful engagement with technology is a part of having the maker mindset. He notes that play, fun, and interest are core to making and are considered a fundamental developmental activity for children and adolescents. Playful activities are said to improve persistence in the face of challenge, and encourage experimentation (Piaget, 1973; Vygotsky, 1987). Martin (2015) also remarks that many makers are motivated not by professional desires, but in their own personal pleasures in making and using their own inventions.

Failure-positive – Martin (2015) notes that failure is part of making and is often celebrated in the Maker Movement. Based on this, he suggests that developing a failure-positive attitude towards overcoming obstacles when building projects is part of the maker mindset.

3 https://www.arduino.cc/
4 http://www.makeymakey.com/

Collaborative – Martin (2015) suggests that collaborative nature is part of being a maker. He states that, "the collaborative nature of the maker mindset comes from an embrace of sharing ideas and projects, and helping others" (Martin, 2015, p. 8). However, this is not just limited to working on a shared goal together but also related to building a community – one that works collectively to build and share new knowledge (Scardamalia and Bereiter, 2006).

2.1.4.3 *Making*

Roedl et al. (2015) in their discourse analysis of 191 papers related to Maker Culture found two distinct definitions of making. The first, *near-universal human activity*: a practical everyday means of making do and making sense in the world. For example, the creative appropriation of artifacts in the home (Wakkary and Maestri, 2007). The second, *hobbyist activity*: enthusiasm to make to represent subcultural identities and lifestyles. For example, the Steampunk movement where individuals build artifacts that evoke an imagined alternative past, present, and future (Tanenbaum et al., 2012). More recently, a third distinct definition of making has been discussed in the area of Maker Education, *educational activities*: a self-directed problem-based or project-based activity that relies upon hands-on, often collaborative, learning experiences (Honey and Kanter, 2013). For example, in the book *Design, Make, Play* (Honey and Kanter, 2013), an example of educational activity is bicycle pump modified to act as a marshmallow cannon capable of shooting a marshmallow 175 feet.

Based on these definitions, in the broadest sense, the term making refers to all practices of tinkering, craft, technology appropriation, and learning (Dougherty, 2013; Roedl et al., 2015). **In this dissertation, we use the term making to refer to building personally meaningful physical computing projects by oneself**.

2.2 MATERIALS FOR MAKING

In the previous section, we discussed benefits of hands-on activities and discussed the different aspects of the Maker Movement. In this section, we present an overview of research that discusses the materials used by makers for building physical computing projects.

The classic materials used in traditional making-centered activities such as home craft include wood, paper, and paint (Buechley and Perner-Wilson, 2012). However, with the evolving research in material sciences, computational media, and very broadly technology, the landscape of materials for making-centered activities has expanded (Eisenberg, 2004). Below we briefly discuss four categories of materials that are common to physical computing projects: (1) hardware and electronics, (2) constructionist toolkits, (3) prototyping tools, and (4) programming environments.

2.2.1 *Hardware and Electronics*

Eisenberg (2004) discussed three classes of hardware materials for making: (1) Output or Responsive materials – materials that display information, or transform electrical signals (e.g. temperature sensitive materials, shape-memory alloy); (2) Input, Sensing, or Communicative materials – materials that communicate signals to (or perhaps between) computers (e.g. piezoelectric materials, optical fibers); and (3) Miscellaneous materials – hobbyist materials that are neither input nor output (e.g. plastic, aerogels).

A variant of this categorization was discussed by Buechley and Perner-Wilson (2012) specifically for creating electronics-based craft: (1) connectors, which route electricity from place to place; (2) inputs (or sensors) that capture information from the environ-

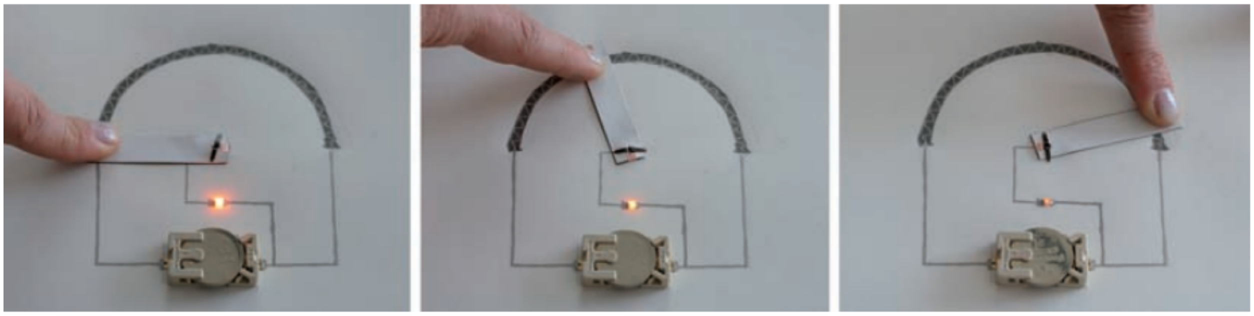


Figure 6: Painted circuit using conductive ink (Buechley and Perner-Wilson, 2012).

ment; and (3) outputs (or actuators) that display information. Using the three categories of components, the authors discussed creating craft via carving, sewing, and painting and drawing. For example, in Figure 6, a paper craft is created by drawing connections between input (knob) and output (LED) components using conductive ink.

2.2.2 *Constructionist Toolkits*

Constructionist toolkits are hardware and software platforms that allow makers to build physical computing projects. To present an overview of the different kinds of constructionist toolkits available for makers, in this section, we summarize the historical analysis of microcontroller-based kits and physical computing devices discussed by Blikstein (2013b).

2.2.2.1 *The First Generation*

The first generation of constructionist toolkits consists of the LEGO/Logo (Resnick et al., 1988), Logo Brick and Braitenberg Bricks (Martin, 1988), and the Programmable Brick (Resnick et al., 1996). LEGO/Logo system is a building set consisting of LEGO pieces and a computer interface including sensors, motors, and control (Logo programming).

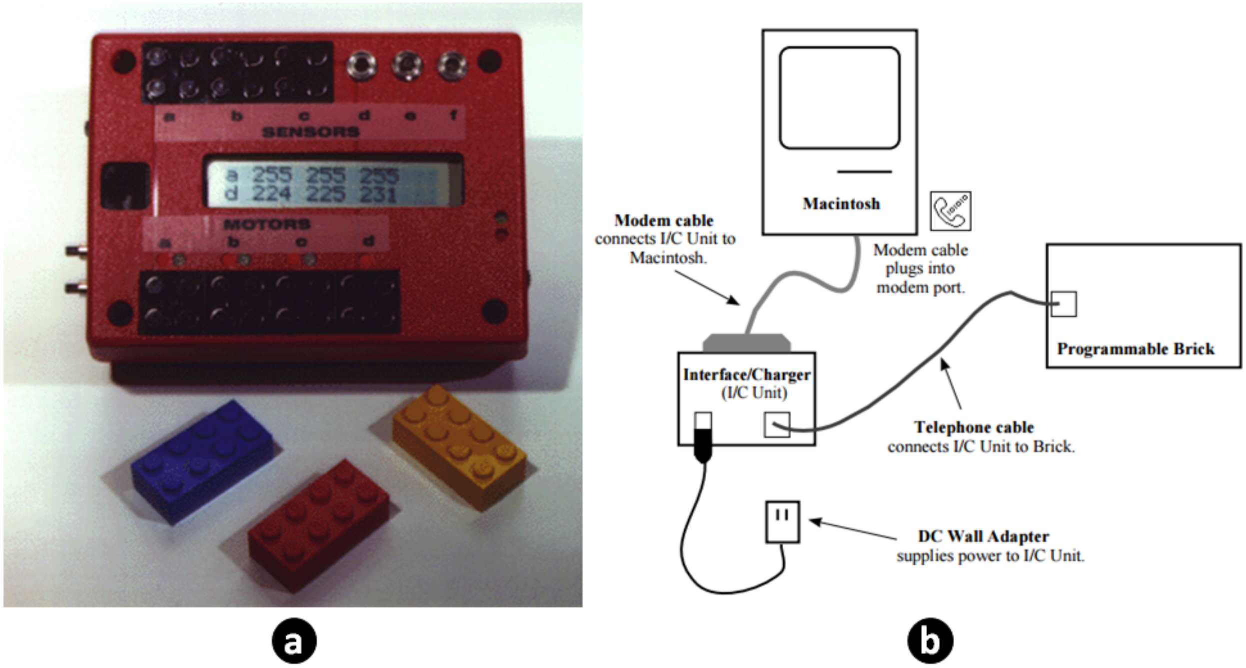


Figure 7: Programmable Brick: (a) System and (b) Interface (Resnick et al., 1996).

Using the LEGO/Logo system children could build LEGO machines and then program behaviour of the machine by manipulating the sensors and motors. The Logo Brick extended the LEGO/Logo system and implemented a system where the processor resides inside of a LEGO brick. To extend the functionality of the Logo Bricks, Martin (1988) developed the Braintenberg Bricks. The Braintenberg Bricks are a set of hardware bricks (e.g. light sensor brick, motor driver brick, flip-flop brick) that can be connected to the Logo Brick. Many Braitenberg Bricks had to be connected together to implement complex functions. The Programmable Brick (Figure 7) overcame the limitation of connecting multiple bricks by embedding a fully programmable computer into a LEGO brick. The Programmable Brick had several design goals – support a wide variety of different activities, support multiple inputs and output modalities, support parallel processing, and lastly,

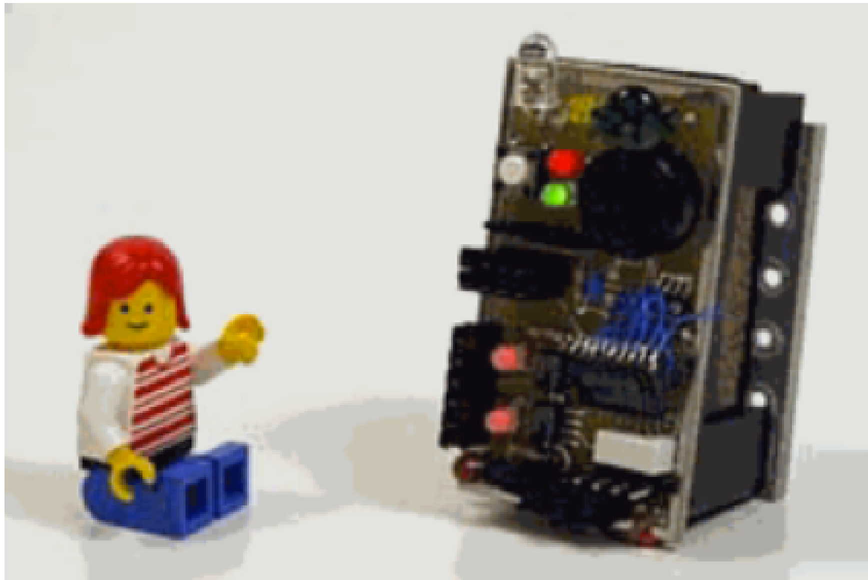


Figure 8: Cricket (Resnick, 1998).

support multiple Programmable bricks to share sensor data with each other (Resnick et al., 1996).

The common underlying design principle for first generation of toolkits was to create a platform that enables children to learn powerful ideas through design and about design (Resnick et al., 1996). The idea was to bring Papert's constructionist theories (Papert and Harel, 1991) to classrooms – children could design and invent, and be "actively involved in creating and constructing meaningful products" (Resnick et al., 1996). Over the last decade, this idea has come back to gain popularity with the Maker Education concepts.

2.2.2.2 *The Second Generation*

The second generation consists of the LEGO Mindstorms, Cricket (Resnick et al., 1988, 2000), and other projects that extended the LEGO/Logo and the Programmable Brick. Crickets, developed by Resnick et al. (2000), are small, fully programmable computational devices (Figure 8) that students can embed in (and connect to) everyday objects. Another example is the BASIC Stamp, a microcontroller-based board with sensors and outputs. Unlike the Logo-based boards up until this point, the BASIC Stamp had to be programmed using the Basic programming language. The language was more powerful than Logo, but much harder to learn.

Three interesting design principles emerged from the second generation. Crickets introduced the design principle of “digital manipulatives" (Resnick et al., 2000): a way “to expand the range of concepts that children (and adults) can explore through direct manipulation of physical objects” (Resnick, 1998, p.44). The main goal was to leverage traditional toys to introduce a new capability that would expose children to new ideas. Another design idea introduced by the Cricket platform was to build devices that go “beyond the black boxes” (Resnick et al., 2000, p. 4): tools and project materials that students could use to create, customize, and personalize their own scientific instruments (Resnick et al., 2000). Lastly, the BASIC Stamp platform introduced the design of the “breakout" model (Blikstein and Krannich, 2013, p.6). Unlike other platforms so far, the BASIC Stamp board exposed one extra hardware layer – the pins of the microcontroller.

2.2.2.3 *The Third Generation*

The third generation consists of microcontroller kits such as the Curlybot (Frei et al., 2000), MetaCricket (Martin et al., 2000), Phidgets (Greenberg and Fitchett, 2001), GoGo Board (Sipitakiat et al., 2004), and Arduino. The third generation introduced ideas such as program by example (Frei et al., 2000), modularity (Greenberg and Fitchett, 2001), low-cost open-source devices (Sipitakiat et al., 2004).

The Curlybot is an autonomous two-wheeled vehicle with embedded electronics that can record how it is moved and play back the recorded motion repeatedly (Figure 9) (Frei

Figure 9: MIT Curlybot (Frei et al., 2000).

et al., 2000). It was developed to be a digital manipulative for children ages four and up. To make concepts of programming and mathematics more accessible for children Curlybot used a technique called *program by example* – children would perform actions with Curlybot, which was recorded and later played back.

Phidgets developed by Greenberg and Fitchett (2001) are modular boards designed to make developing physical interfaces easier for programmers and designers (Figure 10). The BASIC Stamp model and the Cricket platforms motivated the Phidgets design. The goal for Phidgets was to enable designers to spend more time on actual physical interface design and less on low-level electronics design. To achieve this goal, Phidgets incorporated the idea of modularity. Electronic components could be easily plugged into the microcontroller board, and a high level API enabled easy access to the components for

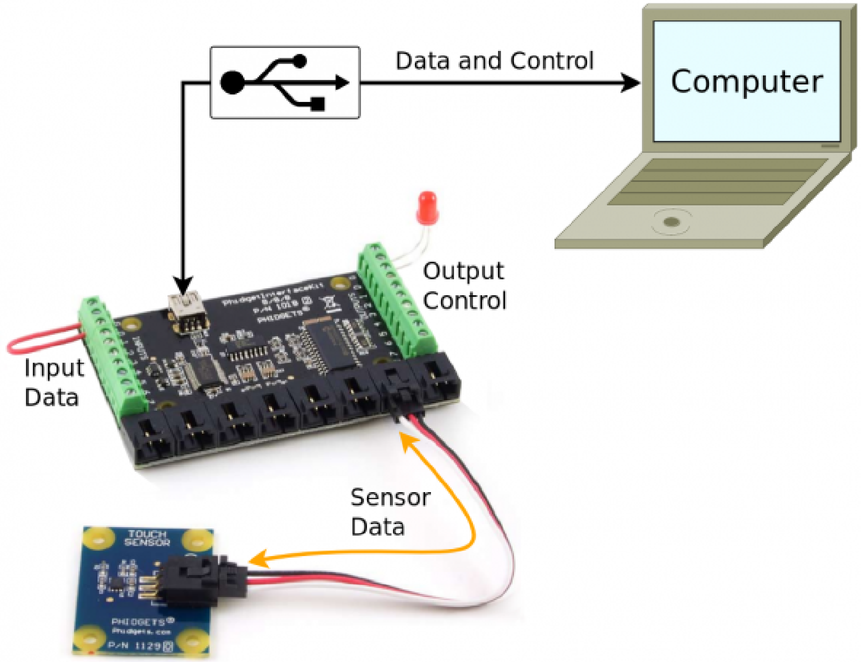


Figure 10: Phidgets (Greenberg and Fitchett, 2001).

programming. Phidgets were originally marketed for older students and professionals, but have also been used in schools and physical computing workshops for children.

Unlike the research in construction kits we discussed above, Sipitakiat et al. (2004) started a new line of construction kits intended for learners in developing countries. Sipitakiat et al. (2004) argued that the previously developed microcontroller kits were not accessible to much of the developing world. Kits such as the Programmable bricks were expensive, and hard to find. To address some of these issues, GoGo board (Figure 11) was developed to be locally assembled on site by the user and made use of electronics that could be easily found in the local markets of countries liked Brazil, Mexico, and Thailand. The design was open-source, and therefore, designers in different countries could adapt the board to their own needs. Another benefit of the GoGo board was that it allowed for use of found and broken electronics.

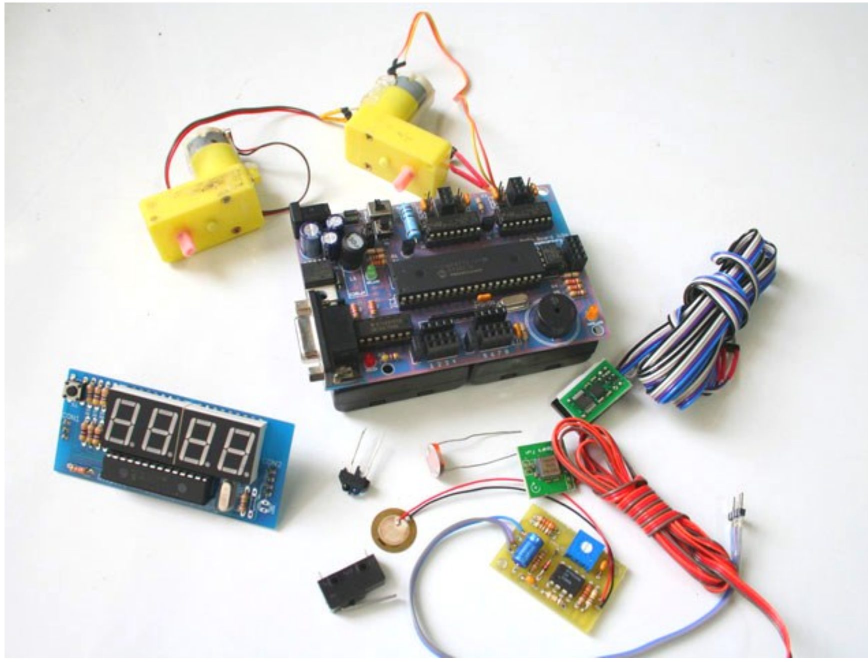


Figure 11: GoGo Board (Sipitakiat et al., 2004).

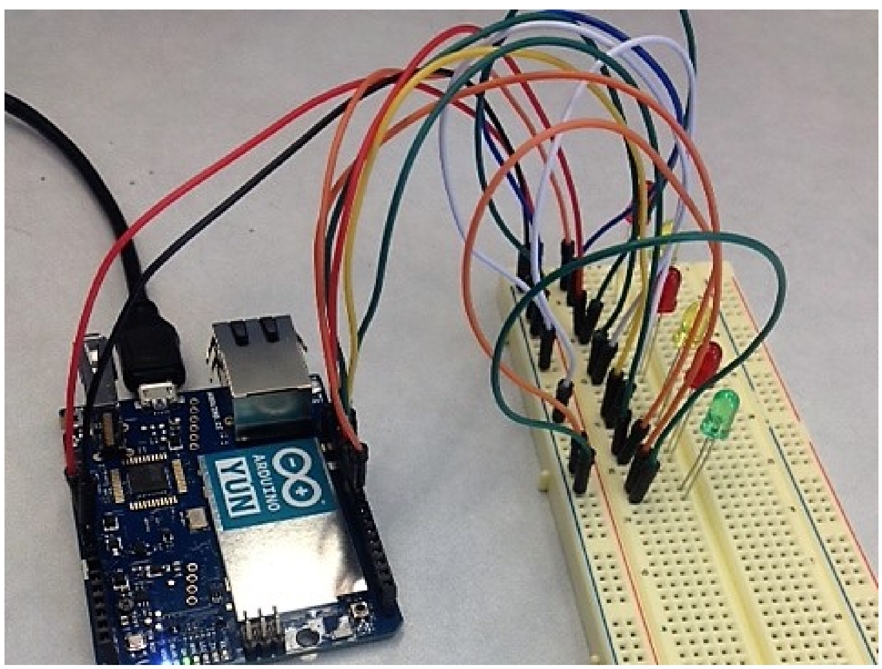


Figure 12: Arduino.

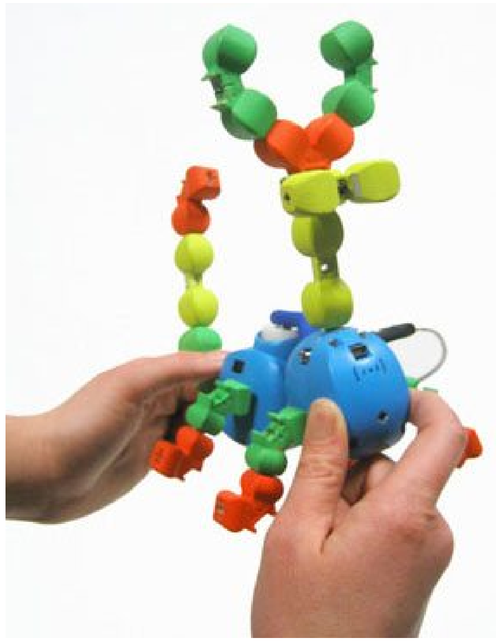


Figure 13: Topobo (Raffle et al., 2004).

Another open-source kit from this generation is the Arduino (Figure 12). Arduino kit is a commercial kit based on the Wiring platform developed by Barragán (2004). Arduino is similar in design to the BASIC Stamp, and exposes the microcontroller pins to the users directly. When using the Arduino, makers build circuits externally on breadboards using wires and electronic components. The Arduino is open-source and relatively low cost compared to the other platforms from this generation.

2.2.2.4 *The Fourth Generation*

Lastly, the fourth generation consists of construction kits such as the LEGO NXT, Handy-Board BlackFin, PICO Cricket, Topobo, Robo-Blocks, Arduino LilyPads, MaKey MaKey and littleBits. The focus of the fourth generation is new form factors and new architectures. The LEGO NXT, HandyBoard BlackFin, and PICO Cricket were based on their predecessors in generations one to three. Unlike these three, Topobo and Robo-Blocks

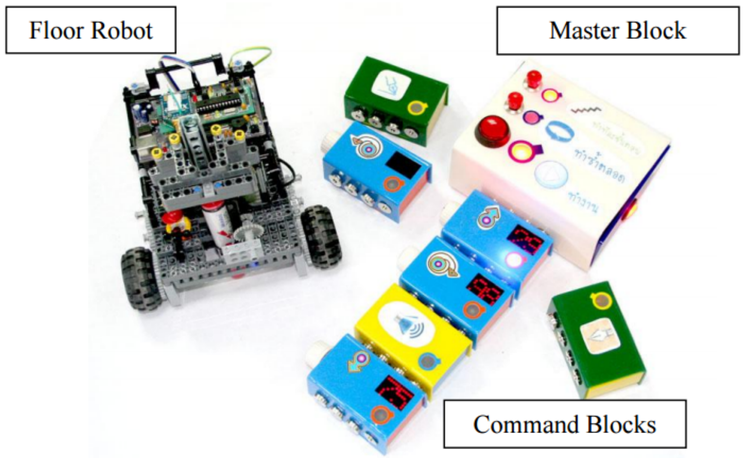


Figure 14: Robo-Blocks (Nusen and Sipitakiat, 2011).

focused on exploring modularity in design. Topobo, developed by Raffle et al. (2004) is a 3D construtive assembly system with kinetic memory (Figure 13). Similar to the Curlybot, Topobo has the ability to record and play back physical motions. The main design feature of the Topobo is a set of passive and active components that can be assembled together to create dynamic biomorphic forms like animals and skeletons. By pushing, pulling, and twisting the components, the assembled form can be animated. For example, a toy dog can be constructed and then taught to walk by twisting its body and legs. Two other examples of a modular system in the fourth generation are the Robo-Blocks (Nusen and Sipitakiat, 2011) and littleBits (Bdeir, 2009). Robo-Blocks is a tangible programming system. It consists of a set of modular command blocks that can be connected together to program the movement of a floor robot (Figure 14). littleBits are a set of discrete electronic components. The components can be snapped together to build a variety of projects (Figure 15).

Different from the other examples in this generation, the LilyPad Arduino by Buechley et al. (2008), introduced a new sewable construction kit (Figure 16). The main goal for

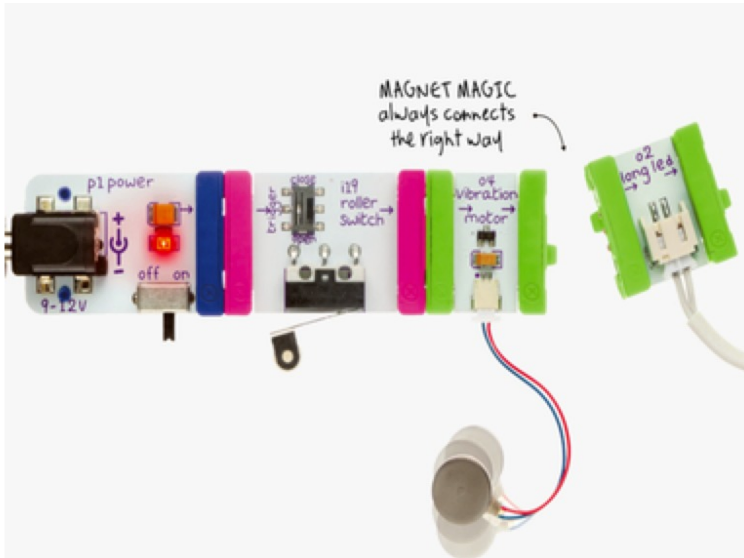


Figure 15: littleBits (Bdeir, 2009).

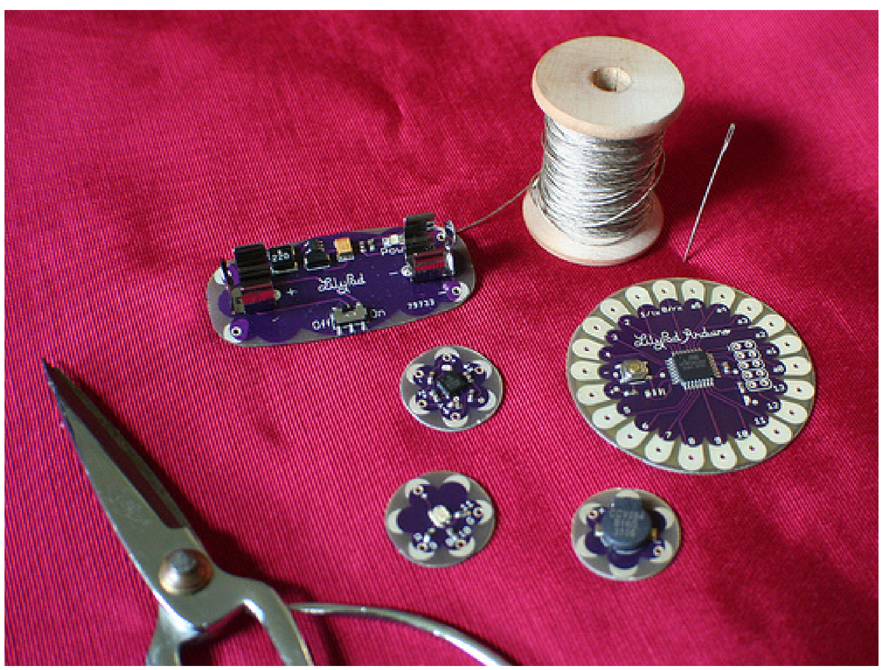


Figure 16: LilyPad Arduino (Buechley et al., 2008).

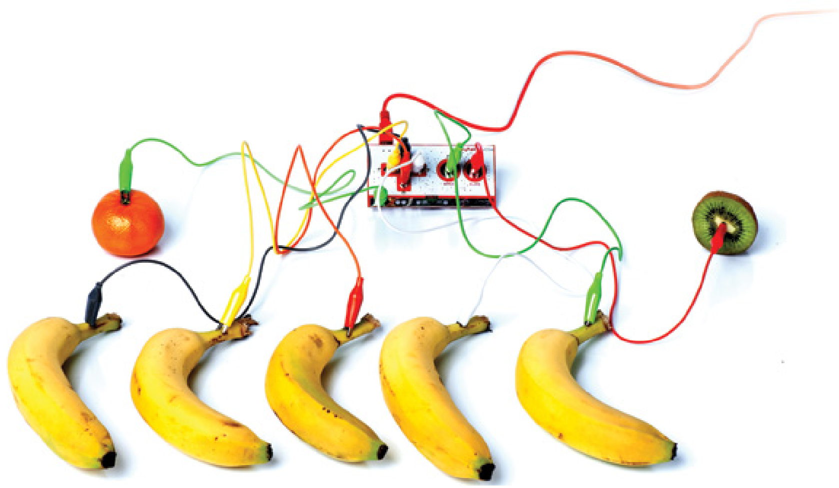


Figure 17: MaKey MaKey (Collective and Shaw, 2012).

the LilyPad was to propose a new hardware platform focused on empowering females. The idea was to engage a diverse range of students in engineering and computer science in physical computing by providing a new medium that allows them to build e-textile projects. To build an e-textile project, people sew components of the platform together with conductive thread and then program the microcontroller using the Arduino environment.

Another example of new form factors and new architectures is the MaKey MaKey (Collective and Shaw, 2012). MaKey MaKey enables people to create different user interfaces with a wide variety of found objects without requiring people to program or assemble electronics (Figure 17).

In our studies, we used three commercially available constructionist toolkits: Arduino, LilyPad, and MaKey MaKey. In the study conducted in India (Chapter 3), our participants used the Arduino to build open-ended projects. In the Maple study (Chapter 4), our participants were exposed to the LilyPad, MaKey MaKey, and Arduino. Our choice of tools was based on the goal of our study and previous literature. For example, based

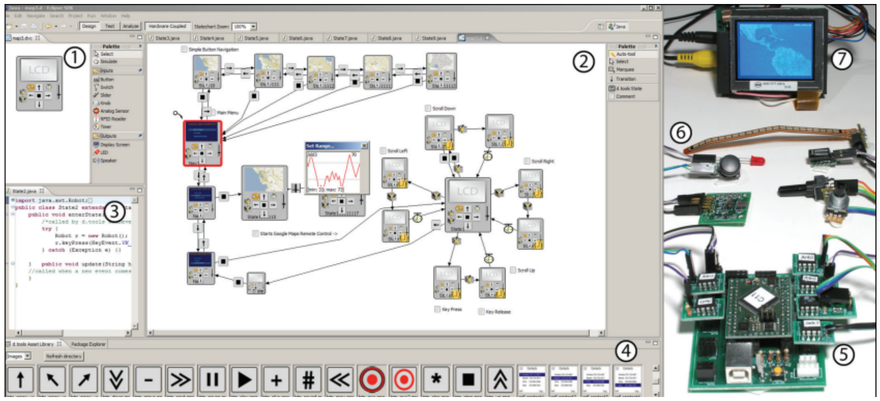


Figure 18: d.tools authoring enviornment: (1)-(4) visual programming enviornment, (5)-(7) hardware interface (Hartmann et al., 2006).

on the use of GoGo board for economically-constrained context (Sipitakiat et al., 2004), we used a similar commercially available toolkit, the Arduino, for our study in India. Similar to GoGo board, Arduino is open-source design and allows people to connect other off-the-shelf hardware components to the microcontroller, making it a viable option for long-term use in an impoverished school. Similarly, LilyPad was previously used in a study with "at-risk" youth (Kuznetsov et al., 2011) as a means for therapy.

2.2.3 *Prototyping Tools*

For building interactive systems, designers iterate and create prototypes. Prototype is a concrete representation of part or all of an interactive system (Beaudouin-Lafon and Mackay, 2003). The tangible prototype representation allows developers to envision and to reflect upon the final system. In this section we review research projects that discuss two sub-categories of prototyping tools for making-centered practices.

Figure 19: Makers' Mark (Savage et al., 2015).

2.2.3.1 *Authoring Environments*

d.tools (Hartmann et al., 2006) is an authoring environment for physical prototyping that combines visual programming of application logic with a novel plug-and-play hardware platform (Figure 18). Designers begin by plugging physical components into the d.tools hardware interface and then author behaviour digitally using a statechart-based visual programming interface. The learner triggers the interaction model by either interacting with the physical electronics or by simulating the electronics virtually.

Makers Mark's is a system that allows makers to create complex TUIs (Savage et al., 2015). To build a TUI, first the maker creates a physical object and annotates the object using stickers that represent functional objects (e.g. button, joystick, hinge, knob, raspberry pi etc.) as shown in Figure 19. Next, the maker scans the created geometry. Using the 3D scanned model, the system creates a new model by hollowing out the model in the maker positions. Lastly, the maker prints the modified 3D model, places the real electronic components in the hollow spots, and finally builds and programs the circuit.

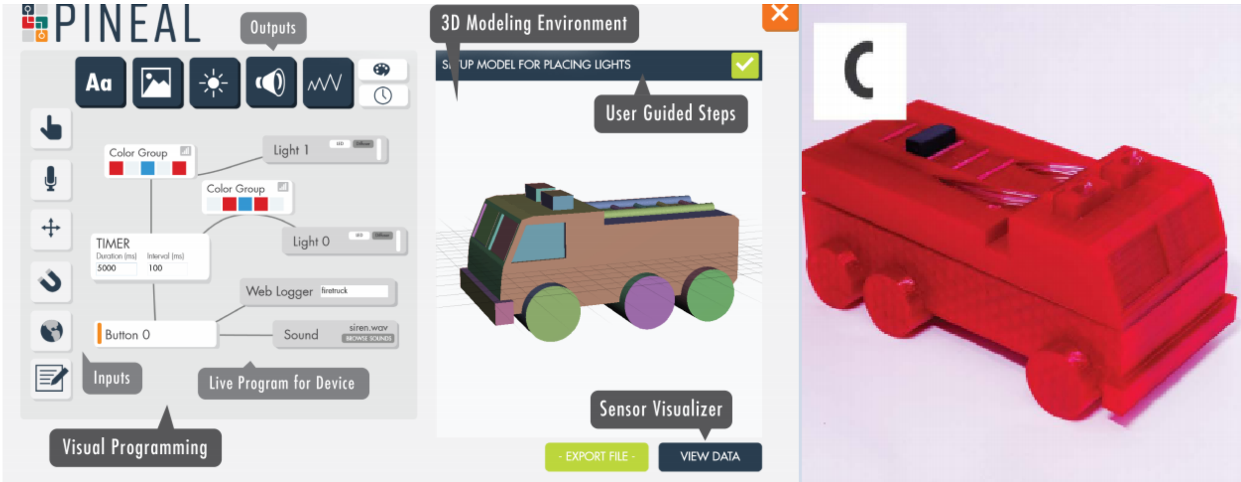


Figure 20: Pineal interface and smart object created with Pineal (Ledo et al., 2017).

Pineal, by Ledo et al. (2017) is a design tool that lets end-users create smart objects using a smart phone or watch as the main controlling device. To build a smart object prototype, first, end-users modify 3D models to include a smart watch or phone. Next, they specify high-level interactive behaviours through visual programming. Finally, the person can interact with the input components (e.g. button) on the smart object and the embedded phone or watch triggers the programmed behaviours (Figure 20).

2.2.3.2 *Augmented Reality Tools for Physical Computing*

Several projects, such as AR circuits (AR circuits, 2016), LightUp (Asgar et al., 2011; Chan et al., 2013), MixFab (Weichel et al., 2014), and ConductAR (Narumi et al., 2015) have explored the use of augmented reality (AR) technique to help with physical computing projects.

AR Circuits (AR circuits, 2016) is a commercial educational app, which uses AR to build circuits without any electronics (Figure 22). Learners' assemble printed-paper com-

Figure 21: LightUp interface (Chan et al., 2013).

ponents (e.g., battery, wire, bulb, switch) together to build virtual circuits. Learners can interact with the components in their circuits, but cannot program the circuit.

LightUp is an AR application that recognizes the circuit behavior and gives live and interactive graphic feedback (Asgar et al., 2011; Chan et al., 2013). LightUp helps children explore engineering and electronics by foregrounding fundamental concepts. It consists of special electronic components mounted on blocks that connect to each other magnetically to form circuits. The mobile app serves as an "informational lens" providing information about circuit behavior (Figure 21).

MixFab is a mixed-reality environment that helps users design objects in an immersive AR environment for 3D fabrication (Weichel et al., 2014). The immersive AR environment enables creating objects, interacting with the virtual objects, and the introduction of physical objects into the design of the object (Figure 23).

ConductAR is an AR tool that can recognize and analyze hand-drawn, printed, and hybrid conductive ink patterns (Narumi et al., 2015). The augmentation helps users to understand and enhance circuit operation. The tool automatically calculates the resistance

5 Source: http://arcircuits.com/#preview

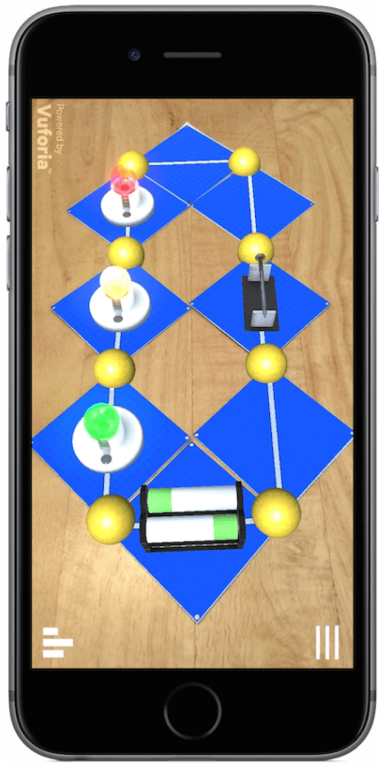


Figure 22: AR Circuits[5].

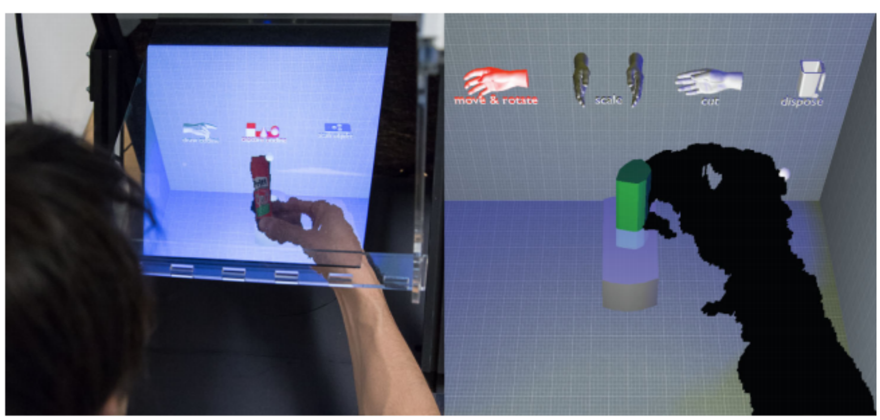


Figure 23: MixFab Interface (Weichel et al., 2014).

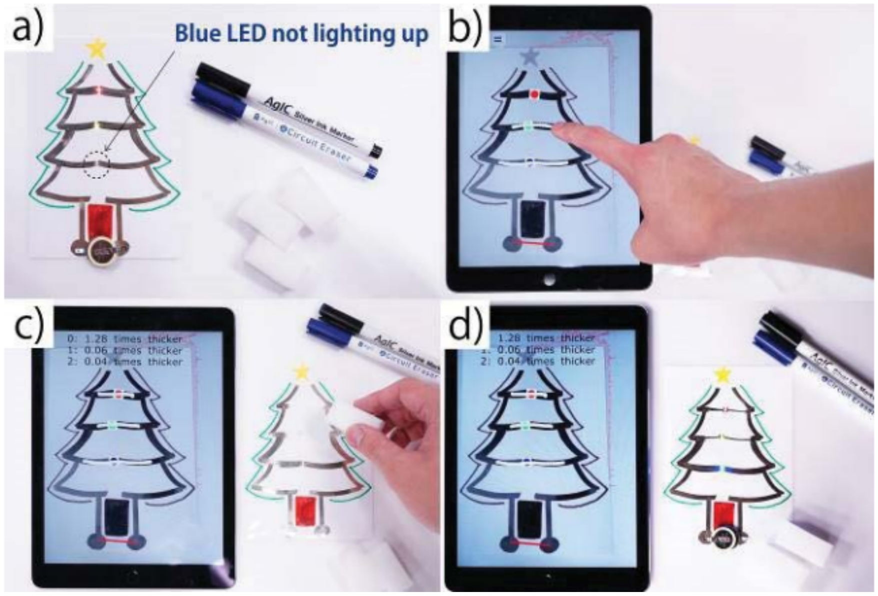


Figure 24: ConductAR interface (Narumi et al., 2015).

across different segments of the hand-drawn circuit. Based on the resistance calculation, the AR system suggests ideal line width to adjust voltage for the electronic components in the circuit.

In this dissertation, we envision AR-mediated prototyping as a way to allow makers to continue building physical computing projects despite a lack of materials (Chapter 5). We designed and developed a tool, Polymorphic Cube (PMC) based on our vision (Chapter 5). PMC is inspired by several of the prototyping tools described above.

2.2.4 *Programming Tools & Environments*

Programming is an important part of building physical interactive systems. In this section we review two sub-categories of programming tools and environments.

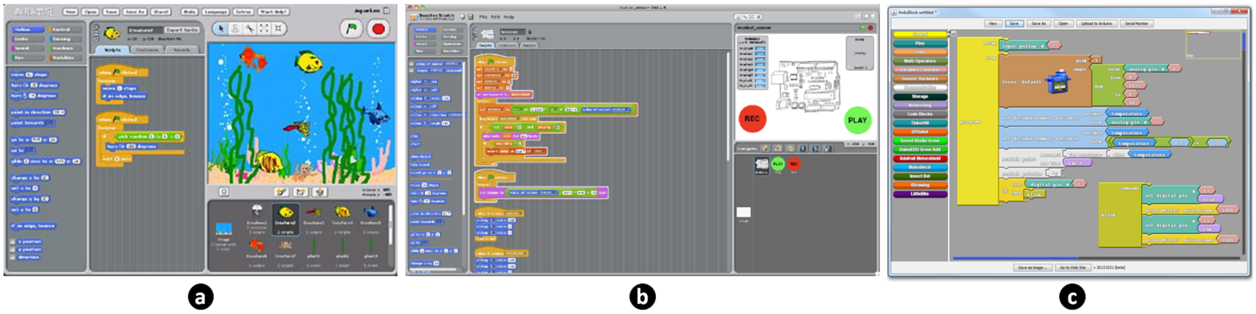


Figure 25: Examples of Visual Programming Languages: (a) Scratch (Maloney et al., 2010), (b) S4A, and (c) ArduBlock.

2.2.4.1 *Visual Programming Environments*

Simplified graphical, block-based programming environment is common to several tools for makers (e.g. d.tools (Hartmann et al., 2006) and Pineal (Ledo et al., 2017)). Visual programming environments are said to be useful to empower users by "hiding" or encapsulating the technicalities (Kelleher and Pausch, 2005). Visual programming is also said to be easy to parse and understand for novice learners and young coders (Kelleher and Pausch, 2005).

One very popular visual programming environment is the Scratch programming environment (Resnick et al., 2009; Maloney et al., 2010). Scratch is developed for young learners, ages 8-16, to learn programming by writing code for personally meaningful projects such as animated stories and games. To create a program in Scratch, learners assemble blocks of code which are then executed in a linear fashion (Figure 25a). To encourage self-directed learning, Scratch includes many design features (Maloney et al., 2010). For example, Scratch interface strives to make navigation easy by using a single-window interface. Scratch also supports "liveness" and "tinkerability" by allowing learners to create and test small program fragments and modify code blocks without the need to switch to edit mode.

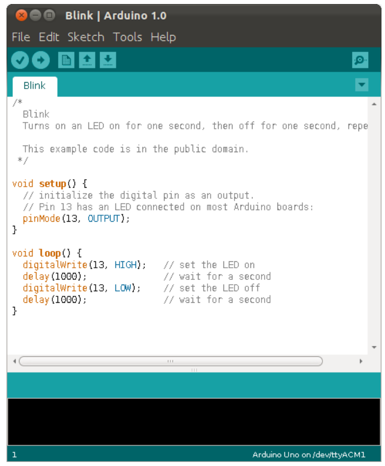


Figure 26: Arduino IDE.

Others have adapted Scratch to better support programming electronics. For example, Scratch for Arduino (S4A) [6], is a modified Scratch platform for simple Arduino programming (Figure 25b). ArduBlock [7] is another Scratch-based visual programming platform designed to make physical computing easy (Figure 25c).

2.2.4.2 *Integrated Development Environment*

Another, more "techno-centric" (Kelleher and Pausch, 2005) approach to programming is using integrated development environment (IDE). The main purpose of IDEs is to teach programming. The emphasis is on technical aspects such as function calls and syntax. For example, the code consists of the use of function calls such as "digitalRead" and "digitalWrite" to read and write values from and to the microcontroller. The Arduino IDE [8] is a popular example in this category for building electronics-based projects (Figure 26). Using the Arduino IDE, programmers write code using the C/C++ language.

6 http://s4a.cat/
7 http://blog.ardublock.com/
8 https://www.arduino.cc/en/Main/Software

2.3 Previous studies of making within constraints

Numerous researchers have conducted observational studies of current maker practices (e.g. Buechley et al., 2008; Kuznetsov et al., 2011; Kafai et al., 2014; Sun et al., 2015; Lin and Shaer, 2016; Meissner et al., 2017). In this section, we review previous studies related to making within material, cultural, and emotional or behavioral constraints.

2.3.1 *Material Constraints*

Research exploring ideas of constructionist and project-based learning has been done with impoverished communities in the learning science and education fields (e.g., Blikstein, 2008; Cavallo et al., 2004; Sipitakiat, 2001; Barton et al., 2016). Specifically related to physical computing activities, Sipitakiat et al. (2004) explored the use of GoGo board (discussed in Section 2.2.2), in an economically challenged context (Brazil). From the ethnographic studies conducted using the GoGo board, Sipitakiat et al. (2004) found that cost constraints and limited availability of hardware are potential challenges for promoting physical computing activities in impoverished communities of Brazil. The authors suggested locally manufacturing the microcontroller board to reduce costs, and to re-use found and existing materials such as broken electronics to encourage exploration of readily available technology (e.g. clocks and radios).

2.3.2 *Educational Culture Constraints*

Research into how educational culture affects technology-based making-centered activities is a less explored area. Related to physical computing activities, Mukherjee (2002) explored hands-on learning in a school in India and posited that a constructivist approach to learning could benefit students trained in "textbook culture" (Kumar, 1988). The textbook culture suggests that the main source of knowledge is a textbook. In an examination driven school culture, following the textbook culture implies that the students are required to memorize the content of the textbook (rote learning) and reproduce the same in an examination. Because of prevalent rote learning culture, students have very limited direct hands-on experiences. Mukherjee (2002) hypothesized that by introducing students to hands-on activities such as BRiCS (build robots create science), students' practical knowledge and understanding of educational concepts can be improved.

2.3.3 *Emotional or Behavioral Constrains*

Several researchers have introduced making-centered activities to learners within emotional or behavioural constraints. Kuznetsov et al. (2011) introduced e-textile activities as therapy and for mentoring of at-risk students. They found that the e-textile workshop sessions inspired their participants, who tended to be uninterested and uncooperative in educational activities, to complete interactive projects and engage with workshop volunteers as mentors and peers.

Stager (2013) introduced the concept of Constructionist Learning Laboratory (CLL) to engage youth in prison facilities. The design goal of CLL was to create an environment that mimics the principles of constructionism (Papert and Harel, 1991), wherein, youth engaged with a wide range of low and high-tech materials (e.g. LEGO, Arduino) to build physical artifacts. CLL students engaged in learning-by-making and students who were thought to be incapable of learning proved quite capable and even enrolled in college courses while in the CLL.

Lin and Shaer (2016) conducted a case study to explore how technology toys can promote computational thinking for young children in Cape Town. They explored the use of littleBits with elementary school children from diverse socioeconomic backgrounds. They found the main challenges for South African children to be peer pressure, low self-esteem, and unequal treatment from teachers. In contrast to privileged students, children of impoverished communities were observed to exhibit important differences. They had a lower frequency of communication and primarily relied on non-verbal communication, affecting the social aspects of making. They also had less of a gender divide for DIY-based activities. Lastly, thanks to littleBits, they had a new opportunity to develop fine motor skills and practice basic language skills (e.g., using prepositions to describe their circuit).

Our studies (discussed in Chapters 3 and 4) are inspired by these existing works and contributes to this body of work by exploring how makers respond to making within constraints.

2.4 SUMMARY

In summary, Chapter 2 covered the background relevant to the entire dissertation. In this dissertation, we are inspired by many of the works presented in literature, and contribute to this body of work by: (1) conducting studies, which shed light on how people make within material, education culture, and emotional or behavioral constraints, and (2) designing, developing, and evaluating a new tool to address making within material constraints.

3

EXPLORATORY STUDY OF YOUNG LEARNERS USING ARDUINO AT A HIGH SCHOOL IN INDIA

Making-centered activities in schools (e.g., Kafai et al., 2014, 2013; Martinez, 2013), and out of school outreach activities (e.g., Ladies learning Code, 2017; Make:, 2016) has increased and broadened participation in the Maker Movement. A general emphasis has been placed on the idea that every child can become an innovator (e.g., Dougherty, 2013; Halverson and Sheridan, 2014). However, not all children have the resources or support they need to innovate (e.g., Sipitakiat et al., 2004; Barton et al., 2016; Lin and Shaer, 2016). The overarching goal of this research project is to explore what happens when there are systematic infrastructural and cultural limitations that inhibit Maker Culture from taking hold.

An impoverished school in India is a prime example of a context with both economic and rigid educational culture constraints that challenge several assumptions of Maker Culture – for example, easy access to technology, abundant independent learning resources, and the intellectual ability of a student to independently select and solve problems. Within these constraints, we explore how young learners in India respond to the innovation and self-directed learning fostered by making-centered activities.

In this chapter, we present an observational study of a making-centered workshop conducted at the Kar School (a pseudonym), a high school in peri-urban Bengaluru, India. Twelve (6 girls, 6 boys) grade 8 students (13-15 years old) participated in our three-day workshop and used the Arduino to prototype beginner level project ideas. We adopted a similar study methodology to what has been previously explored in other workshops (e.g., Buechley et al., 2008; Kuznetsov et al., 2011). We observed, engaged in the participant projects, and conducted informal interviews with the participants. The results of our observations and informal interviews from both during and after the workshop indicate that students at the Kar School face psychological cost to exploration, have limited independent learning resources, struggle to find the necessary intellectual courage to explore, and have technical barriers to engage in making-centered activities. However, students are resilient, adopt traditional learning techniques, and make do with the means available to them to overcome some of the challenges.

In the remainder of this chapter, we first discuss the constraints prevalent in schools in India. Second, we revisit related literature. Third, we discuss our study method. Fourth, we discuss our study findings. Last, based on our observations we conclude with a discussion of a set of lessons learned about making within material and cultural constraints.

3.1 IDENTIFYING LIMITATIONS IN THE CONTEXT OF INDIA

The Kar School is a prime example of two forms of limitations prevalent in India, more broadly: 1) infrastructure and educational resource limitations, and 2) cultural resistance to non-conforming DIY activities.

3.1.1 *Infrastructure and Educational Resource Limitations*

Making-centered activities often assume that technology infrastructure (e.g., computers) and educational resources (e.g., documentation, access to books, instructional videos etc.) are readily available. However, an impoverished school in India may not meet this implied requirement. Several articles highlight that rural schools, and sometimes public and private schools in urban cities, can have very poor or sometimes non-existent educational inputs, teaching material or facilities (Cheney et al., 2005; Kingdon, 1996; Muralidharan and Kremer, 2006; Pawar et al., 2006). For example, limited access to computers (particularly in rural schools) is not uncommon. Pawar et al. (2006) pointed out that it is common for several students (sometimes up to ten) to share the same computer. In some schools, a single PC is used as a solo teaching aid; an entire class (30-40 students) crowds around the same computer, ultimately causing the students to lose interest and shift their attention to other things (Pawar et al., 2006). Similarly, students have limited access to educational resources and thus lack the necessary exposure, confidence and knowledge to participate in self-directed DIY activities. For example, the article by Kumar (1988) about "textbook culture" in schools in India notes that resources other than the textbook are not available in the majority of the schools, and where non-textbook resources are available they are seldom used. Teachers fear damaging such resources, and the poor chances of repair or replacement discourage the teacher from using them, in turn limiting students' opportunities to interact with them (Kumar, 1988). These infrastructure and learning resource limitations challenge many of the assumptions of traditional Maker Culture – that people have the resources they need to independently learn how to create things.

3.1.2 *Cultural Resistance to Non-Conforming DIY Activities*

Beyond infrastructure and educational resource constraints, India has a rigid educational culture that includes non-negotiable curricula, a top-down learning approach, limited interaction with teachers, and teacher-centric teaching models. This dominant educational culture actively discourages non-conformist behavior, including innovation and the freedom to explore subjects independently. For example, most schools in India follow a "textbook culture", wherein the textbook is the main source of knowledge for both the teacher and the students (Kumar, 1988). Per this pedagogical approach, the teacher must ensure that students can answer questions based on the textbook without consulting the text during examinations. This examination-driven structure and "textbook culture" encourages rote learning and gaining surface level knowledge, as opposed to deeper analytical or critical knowledge perspectives (Cheney et al., 2005; Kumar, 1988). Mitra et al. (2005) identified the teaching method employed in the majority of schools in India as teacher-centric. A single teacher is in charge of the entire class, and students are not allowed to interact or consult with each other during class time. Students are required to only perform individual learning and complete individual assessments. Mukherjee (2002) observed that such teacher-centric, rote learning is less effective because often students' understanding is limited, distorted or all together wrong. This educational culture is in direct conflict with the student-driven, self-motivated, and discovery-based principles suggested by the DIY approach to problem solving.

3.1.3 *Limitations at the Kar School*

We found both infrastructure and resource constraints as well as traditional educational culture in effect at our study site. We conducted a preliminary observation of one of Kar School's several computer science laboratory sessions. We observed an entire 30 minutes' computer science laboratory session of 15 grade 7 students. This observation was conducted prior to the three-day workshop.

For the laboratory session, a computer science teacher instructed the class in Excel. Although the purpose of the laboratory session was to provide students with hands-on training, the predominant discourse was a one-sided teacher-driven theory lecture. The teacher instructed students to take notes and draw screenshots of Excel menu options, as read from a textbook by the teacher (a classic example of "textbook culture"). During the lecture, students appeared disinterested and easily distracted. During the entire session, no students accessed any of the computers. Further conversations with the teacher revealed that because the lab computers were maintained and updated by an individual outside of the school facility, often the teachers were afraid to let students access computers for fear that the students might damage the computers or disturb the installed software. Within these observed resource limitations and the rigid educational culture constraints at the Kar School we wanted to explore how students react to making-centered activities.

3.2 RELATED LITERATURE

As discussed in Chapter 2, similar research exploring ideas of project-based making has been done with impoverished communities (Sipitakiat et al., 2004; Barton et al., 2016) and

Figure 27: Workshop site: Kar School computer science laboratory.

rigid education culture contexts (Mukherjee, 2002). However, unlike these studies, which focused on hypothesizing benefits of making (Mukherjee, 2002), exploring the design of physical computing kits for economically challenged contexts (Sipitakiat et al., 2004), and developing student identities (Barton et al., 2016), we wanted to understand how students within material and cultural constraints respond – challenges and strategies – to making-centered activities. Our view is that by understanding how makers respond, we can better design tools that not only address problems, but also leverage local strategies developed by people.

Students in India are a unique learner group whose rigid education culture and resource constraints hinder their participation in the Maker Movement. The situational constraints for students at the Kar School actively discourage innovation and independent exploration. In light of our dissertation goal, exploring *making within constraints*, India presents a unique opportunity to gain insights about making within material and cultural challenges.

3.3 STUDY METHOD

We hosted a three-day 'make-a-thon' style (Somanath et al., 2015a) physical computing workshop at the Kar School, a private high school in peri-urban Bengaluru, India. Each day, the workshop lasted three hours and students engaged in building simple projects using Arduino and other electronics (sensors, actuators, and components). To understand what typical classroom interactions look like at the Kar School we also did a preliminary observation of a computer science laboratory session, as already discussed.

The Kar School is a low-fee charging institution and hence, affordable to students from low social economic status (SES) backgrounds. We conducted the workshop during school hours (9:00 am - 4:00 pm) at the school's only computer lab facility (Figure 27). There are two reasons why we could not conduct the study as a longer after school program. First, the computer lab facility and the school were shut down after school hours. Second, few students (especially girls) were willing to participate in the workshop after school hours due to security concerns, or lack of parental permission. Electricity availability at the school was also limited and unscheduled outages were a common occurrence during the workshop. Due to unscheduled outages, workshop times had to be flexible. The school's faculty had no prior knowledge of Arduino, or about the Maker Movement.

3.3.1 *Participants*

A group of 12 students (6 girls and 6 boys) ages 13-15 years (grade 8) participated in our three-day workshop. The choice of grade 8 students was opportunistic. The school principal selected the 12 participants based on the following criteria. First, because students would miss a total of nine hours of regular class time, the principal wanted to select students who could cope with this break from in-class learning; hence, he chose students who performed academically well among the grade 8 students. Second, we wanted to ensure that the same students could attend all three days of the workshop. As a result, the principal chose students who were also regular attendees at school, ensuring that there was a high probability that all participants would attend the entire workshop series.

From our pre-questionnaire (included in Appendix A), we gathered that all our participants belong to the low SES strata. The participants' parents' occupations can be classified as low-paying jobs that require minimal or no prior education (e.g., building painter, janitor, barber etc.). All but one participant had experience with computers since grade 5; one participant began using a computer during grade 6. Two of the 12 participants owned a personal computer. The most common use of the computers (as specified on the questionnaire) in the school was for using programs such as MS Access and MS Excel (current curriculum). Beyond computers, students had previously interacted with mobile phones that belonged to other family members and two participants personally owned mobile phones. Participants used them for playing games, calling friends and watching videos. There was no explicit mention of using Internet on the phone. When asked about their prior exposure to programming, programming languages, and programmable electronics, 11 out of 12 participants listed English as a programming language. Participants' perception of programming was also quite different from the traditional definition: our participants' equated computer programming to using installed programs on a computer. No participant reported any prior knowledge of electronics and/or programmable electronics.

3.3.2 *Setup*

To observe how young learners at the Kar School would engage with physical computing activities, we provided the resources for this study. The study resources included six Arduino microcontrollers (one Uno R3 and five Leonardo) and a range of electronic components, sensors and actuators (switches, push buttons, resistors, phototransistors, light sensitive resistors, piezo buzzers, servos, vibration sensors, mini speakers, carbon monoxide sensors, temperature sensors, LEDs and force sensitive resistors). The total cost of the electronics purchased was ~$400. Most of the electronics used in the study are accessible within urban India, and can be purchased online and are shipped internationally. We also used Arduinos in our workshop because of their affordance to build a wide variety of projects and rich documentation. During the workshop all the electronics were kept on a central table for participants to freely access. At the end of the workshop, the entire package and additional resources (a copy of the Arduino programming notebook (Evans, 2007) and SparkFun Inventor's Guide (SparkFun, 2017)) were donated to the school for future use by students.

Six computers were used during the study to create a 2:1 student-to-computer ratio. Four out of six computers belonged to the school; the researcher provided two additional laptops. Kar School had a total of ten computers, however, six of the computers were not working at the time of the study. Because multiple users cannot simultaneously build circuits using an Arduino, we used the 2:1 student-to-computer ratio. An increased ratio would more likely cause students to crowd around the single Arduino and a computer, resulting in one student becoming the dominant circuit builder and programmer. Other students would become passive onlookers and perhaps ultimately disengage from the activity (similar to single computer use scenario described by Pawar et al. (2006)).

We installed the Arduino IDE (line programming) and Ardublocks (Ardublock, 2017) (graphical programming) on all computers. As the Kar School had no Internet connection, none of the computers used for the study had Internet access. This setback prevented students from accessing online learning resources. To mitigate the lack of Internet access, the researchers provided a word document with basic sample code for each of the electronic components on all the computers.

3.3.3 *Workshop*

The goal of our three-day workshop was to position the participants as investigators with agency and in turn, to observe how the challenges of the context shaped their DIY experience. The study encouraged discovery-based collaborative learning (Anthony, 1973) wherein, the participants worked in small groups of two or three and helped their peers to debug code and circuit connections. Throughout the workshop period the researcher adopted an inquiry-based learning approach (Alesandrini and Larson, 2002), guiding students by posing questions or problems rather than presenting solutions without much invested effort. The researcher was also available for help; however, because only one researcher was managing the study, their help was also a scarce resource. Throughout the remaining chapter, we reference the researcher as R, participant as P and group as G.

3.3.3.1 *Workshop Day 1*

On day one, the researcher briefly introduced the participants to basic electronics: what is an electric circuit, what is a breadboard and how to build a circuit. The researcher drew a simple circuit diagram on the blackboard to aid the explanation. The researcher demonstrated a practical example of a circuit using an LED and a coin cell battery, showing how to turn on the LED by pressing the LED legs to the positive and negative side of the battery. To familiarize our participants with the Arduino, the researcher walked the participants through a step-by-step LED blinking exercise. Pairs of participants replicated and extended the exercise by connecting multiple LEDs. Participants used the Arduino sample code *Blink* to program the LED. The researcher demonstrated the use of both Arduino IDE and the Ardublocks IDE. After the LEDs were successfully blinking, the researcher gave participants time to continue exploring the circuit connections. After the circuit exploration phase, each group presented to their peers detailing their experimentation process. The researcher used the presentation sessions to probe students' understanding of hardware and software, and to learn how they thought the LEDs blinked. Following these discussions, it became easier for the researcher to clarify and formalize technical concepts such as serial connections and functionality of a microcontroller. Example of a question asked by the researcher during the discussion is as follows:

R: *How did the LEDs turn on and off?*
P7 : *The circuit is continuously going. The current is passing from one bulb [LED] to another, so it is glowing and then shut down, then again it is starting.*

The researcher employed a similar inquiry-based approach to break down parts of the code. The researcher asked participants to share their understanding of keywords such as *setup*, *loop* and *delay*. Based on participants' definitions, the researcher explained the corresponding functions in the code. To provoke the participants to think further, the researcher posed logical questions. For example:

Figure 28: Workshop: Participants working on their projects.

R: *How do you think we can make the LED stop blinking?*

P7: *By removing delay?*

At the end of the session, the researcher briefly explained the functionality of the remaining components. In preparation for the 'make-a-thon', the researcher asked the participants to think of simple project ideas for day two. To inspire the participants, the researcher orally discussed examples of projects that participants could build.

3.3.3.2 *Workshop Day 2*

On the second day, each of the groups presented their project ideas. Presentations were semi-structured asking students to identify the project they wanted to build and briefly list the initial set of hardware they would need to use. The researcher asked questions during the presentations to better understand the group's goal for the chosen project. Participants spent the remaining workshop time building circuits and programming (Figure 28). The researcher encouraged the participants to collaborate and ask peers for help before approaching the researcher. The researcher would eventually help to move them along when necessary. The researcher also asked the groups to make notes of their working process and presentations were conducted at the end of the session summarizing their tasks and challenges for the day. Two groups (G3 and G4) discontinued working on their projects during day two and joined other groups.

3.3.3.3 *Workshop Day 3*

On the final day, four groups completed their chosen projects and did a final presentation of their projects (Figure 29a-d). The workshop closed with an open-ended discussion with the participants. The discussion covered the following topics: participation experience, participants' views of how they benefited from attending this workshop, what they found challenging, and their thoughts on future possibilities for building other physical interactive prototypes.

3.3.4 *Beyond the Workshop: Science Fair*

Six weeks after the workshop, we were informed by the school principal that the school was conducting a science fair. Two workshop participants from G1 demonstrated two electronics projects that they had built for the science fair. The first project demonstrated by G1 was a reconstructed version of their workshop project, a LED calculator (Figure 29a). The second project was a new and independent exploration by G1 (no researcher help) entitled *"Hello World"* (Figure 29e). The student built an array of blinking LEDs arranged to spell "Hello" as seen in Figure 29e. A researcher conducted an unstructured interview during the school science fair to gain insights into the design process and challenges faced by the group.

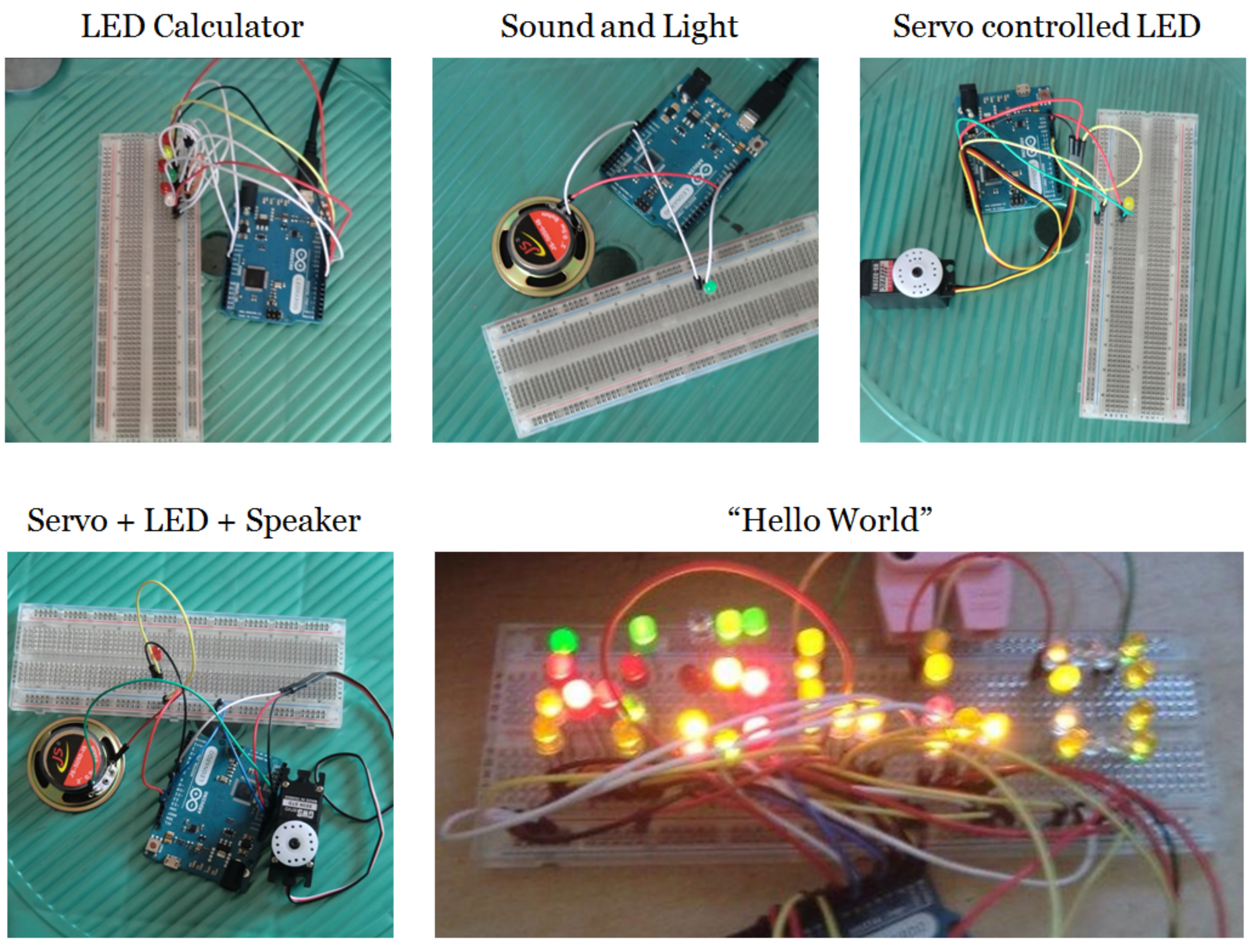


Figure 29: Projects demonstrated at the end of the workshop: (a) LED calculator, (b) Sound and Light, (c) Servo Controlled LED and (d) Servo + LED + Speaker; Project demonstrated at the science fair: (e) “Hello World".

3.3.5 *Data Collection and Analysis*

Data sources for this study included the following:

1. **Pre-questionnaire** – asked personal demographic information and a few questions regarding prior technology and programming experience.

2. **Presentation videos** – at the end of each workshop day we video recorded all participant presentations as they summarized their work, detailing the tasks they had accomplished and how they resolved project related issues. In addition, on day two of the workshop we video recorded all the participants as they presented their project ideas.

3. **Individual group videos** – we used the two laptop web cameras to capture conversations and working processes of two groups.

4. **Written notes from students** – at regular intervals (~2 times per session) each group was asked to write notes about problems they were addressing and a list of any unresolved problems.

5. **Closing discussion video** – at the end of the workshop, we video recorded an informal discussion of the participants' experiences. All workshop participants were part of this discussion.

6. **Informal interview at science fair** - we audio recorded an informal interview with G1 at the school science fair to learn more about their progress after the workshop.

Majority of the collected data was in English. However, parts of the laptop videos were spoken in the local state language (Kannada) and were translated by the researcher

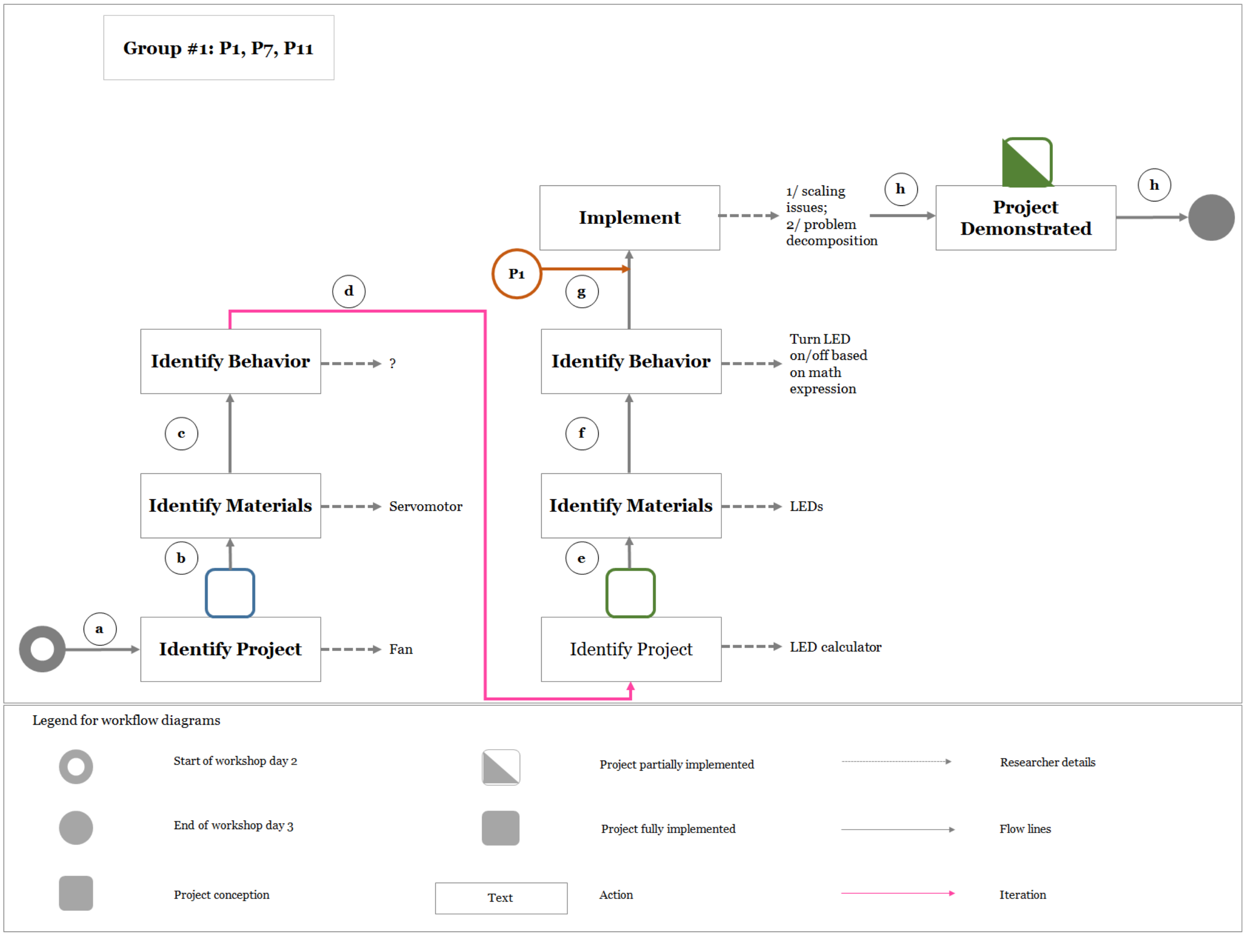


Figure 30: Example workflow diagram (Group 1)

(native speaker). Our qualitative analysis methodology is inspired by Walny et al. (2011) approach. We did several passes through the transcribed video and interview data, and identified the sequence of activities performed. Looking across all group's activities, we created a set of common activity labels. These labels were discussed and revised to arrive at the final set of labels:

1. *identify project*: corresponds to the project proposed by the group;

2. *identify material*: lists the components chosen by the group for their project;

3. *identify behaviour*: describes the expected behaviour of the project as explained by the participants;

4. *implement*: summarizes the main steps taken to implement the project;

5. *project demonstration*: name of the final project demonstrated.

Using the activity labels, we traced each student groups' workshop journey, from project identification to project demonstration as workflow diagrams. For example, Figure 30 shows the workflow diagram of G1. Figure 30 shows that participants P7 and P11 started with proposing to build a fan. However, they did not know what the expected behaviour of their project was, and therefore, decided to explore another idea, LED calculator. While working on the LED calculator, G1 was joined by P1. At the end of the workshop P1, P7, and P11 demonstrated a partially implemented LED calculator project (indicated by partially filled green square). The project required end-users to input a number between 1-6, and based on the input, the correct number of LEDs would turn on.

Guided by the workflow diagrams, we returned to our transcribed video and interview data, and student notes data to identify challenges and student strategies. For example, for G1's workflow we made note of technical challenges such as problem decomposition and difficulties with scaling the project. We have included the workflow diagrams of other groups in Appendix A.

3.4 Challenges to Practising Making-Centered Activities

Within the known resource limitations and cultural constraints prevalent at the Kar School, we observed psychological and situational challenges for students to engage in making-centered activities.

3.4.1 *C1: Psychological Cost to Exploration*

Exploration and tinkering is common to DIY activities (Gutwill et al., 2015; Martinez, 2013). Failure is common, necessary, and fruitful. During exploration and tinkering, learners may fail to accomplish the desired results, may damage the hardware components or may decide to not use a purchased component. However, in a context like the Kar School, there is a high psychological cost associated with trial and error.

In our study, we observed two instances of fear. G3 wanted to build a project using the Arduino temperature sensor. However, G3's attempts at incorporating the temperature sensor failed. The researcher, upon debugging G3's circuit connection, found that the temperature sensor was connected incorrectly and was damaged (the program constantly displayed values in the range of 200°C). After realizing they had broken the sensor, the participants could not be motivated to continue their project and did not want to work with another temperature sensor. To keep G3 involved in the workshop the researcher suggested that the members of G3 join other groups whose projects interested them.

This fear is even apparent when coding software, even though there is very low likelihood of causing irreversible damage through failure. For example, upon G2's circuit building success, the researcher advised G2 to explore the sample program code by modifying the program variables. During this process, the participants would only modify the variable as suggested by the researcher and were reluctant to modify the variables' values on their own. Possible reasons for this hesitation is that G2 may have been concerned that they could not go back to the original code, they did not understand the code or that they did not know what could be modified and how it could be modified. However, irrespective of the researcher encouragement and assurance that they could not "damage" code, participants of G2 did not engage in much free-form code exploration. Similar hesitation with modifying code was also observed in the other groups.

3.4.2 *C2: Limited Independent Learning Resources*

In a typical makerspace, learners have access to several learning resources that help introduce young learners to new educational and computational technologies. These resources may include online learning resources, specialized after school programs, and qualified mentors (e.g., Blikstein, 2013a; Gershenfeld, 2005; Martinez, 2013). However, in a setting like the Kar School, the number of available learning resources is heavily restricted. There was no Internet access available at the Kar School, limiting students from accessing any online documentation. Students did not have any textbooks or guides for physical computing available as a reference. Additionally, teachers at the school were not aware of programmable electronics, and could not mentor or guide the students. The limited availability of independent learning resources challenges several assumptions of how a student can successfully participate in DIY-based activities – How does a novice learner become aware of the idea of making? How do novices learn about physical computing technologies such as Arduino, Makey-Makey and littleBits? How do they understand materials and behaviors? Below we illustrate instances of participants having difficulty with: (a) finding sources of inspiration; (b) understanding how to use and work with technology; and, (c) increasing project complexity due to limited independent learning resources.

Use of independent learning resources such as, online videos and pictures is a common way of inspiring ideas (Herring et al., 2009) and has been used in prior studies (e.g., Kuznetsov et al., 2011). However, students in our workshop had difficulty coming up with ideas because they did not have exposure to outside learning resources. Although proposing new ideas for prototyping is a challenge for any novice learner and has been previously observed (e.g., Kuznetsov et al., 2011)), in our study site it was further emphasized due to limited learning resources. During the workshop 4 out of 6 groups (G1, G3, G5 and G6) proposed to build a fan using a servomotor. Originally the project was proposed by G1, followed by G3, G5 and G6 proposing the same idea. Not having access to resources that could inspire the participants (e.g., showcase of online examples), groups ended up proposing the same ideas. We observed this stagnant ideation again when G5 completed the fan project, but was unable to suggest a new project idea to explore. The researcher had to suggest a new project ("Servo Controlled LED") to allow them to continue exploring.

Understanding hardware and their corresponding behaviour requires some initial documentation input, for example, datasheets or books that explain simple components. Although participants were given a brief introduction to each hardware component being used in the study on day one of the workshop, they had no learning aid that they could use for support. Consulting the researcher was their only source for clarification and learning. Because of this, two groups were seen proposing incorrect project ideas. For example, G2 first proposed to build a project titled "Voice Recording", listing FSR and mini speaker as the required electronic components for this project. The identified behavior was to use the speaker to record the FSR input. However, G2 had no understanding of the distinction between an input and an output device resulting in a flawed behavior identification. The participants were not aware that speaker was an output device and could not be used for recording purposes. Clarification had to be provided by the researcher. Similary, G3 attempted to use a temperature sensor, but wrongly interpreted that 200°C was the correct output for a temperature sensor. The researcher had to re-explain what a temperature sensor was and what the expected output value ranges would be.

Limited resources also make it difficult to increase project complexity or scaling up an idea. Participants had been exposed to connecting one LED to their circuit during day one of the workshop. Scaling from one LED connection to multiple LEDs (required for the LED calculator project) was challenging for all groups. For example, G1 initially connected all the LEDs to the same pin of the Arduino and had no control over individual LED states. Without a reference for concepts like serial and parallel circuit connections, participants were constrained to either solve by trial and error, or ask the researcher. Because our participants were novices, the researcher had to guide them to keep the group moving ahead with their project. Scaling up was also an observed issue for programming. Participants had template code to make one LED blink, however, to change the states of the individual LEDs they had to modify the code accordingly. This was found to be a challenging task as participants did not fully understand how to modify the line code (*"we were having problems in the codes which we were not knowing"* [P7]).

3.4.3 *C3: Finding Intellectual Courage*

Unlike students familiar with an interactive collaborative learning context (Beetham and Sharpe, 2013), students schooled in rigid educational settings like our study site focus on following the teacher instead of independently exploring an educational concept. Rigid educational paradigms like "textbook culture" expect students to memorize textbook content and follow exactly what the teacher proposes (teacher-centric teaching) (Kumar, 1988; Mitra, 2005; Mukherjee, 2002). At the Kar School we observed that students sometimes lacked the necessary intellectual courage to freely explore and learn.

An instance of students' unable to find their intellectual courage was observed on day one of the workshop. After the LED demonstration, participants were given time and were encouraged to explore the circuit. While a majority of the groups explored connecting multiple LEDs to their circuit, G3 was an exception. G3 did not modify their one LED circuit connection. When asked if they wanted to connect more LEDs to their circuit, participants of G3 said *"no"*.

While finding the necessary intellectual courage is a limitation among all groups, particularly G3 who refused to follow others in experimentation, G6 demonstrated unusual intellectual courage for the group. From the laptop videos of G6 we observed that P9 was rather experimental in his approach - *"wait I am doing something, even I don't know what I am doing"* [P9]. Unstructured exploration was characteristic of G6 throughout the workshop - G6 continued to add electronics to their circuit with no explicit goal. Even though they were faced with frustration in the process and the participants felt like they should have done a project similar to others (*"we should have also taken LED project"* [P9]), they strived to keep pushing ahead (*"Don't try to hurry, let's keep trying"* [P12]). This was interesting because although they had no set goal, when G6 found the intellectual courage to explore, they discovered several aspects of circuit building and programming in the process of unstructured exploration.

3.4.4 *C4: Assumed Language Proficiency*

To identify and solve programming errors, students need to understand the syntax of the programming language, and interpret error messages. However, these error messages assume that students have the necessary proficiency with technical English. In places like the Kar School, this assumed language proficiency is yet another barrier for students. This poses a fundamental challenge to practicing DIY-based activities as students who are dealing with unfamiliar English vocabulary will have even more difficulty comprehending the underlying technical concepts behind an error message.

An instance of assumed language proficiency was observed in the video data of G6. Upon uploading the modified template code to the Arduino board, the IDE notified the participants of "precautions" (a compiler notification). However, in order to troubleshoot and isolate the debugger messages the participants have to first understand them. G6 did not understand the meaning of the word precautions (*"let's ask her [the researcher] what is precaution"* [P12]), causing a fundamental block in their progress. Although English is the language of instruction at our study site, this observation shows how technology may prevent people from accessing it when they do not have enough English language proficiency, and much less proficiency in technical language or concepts.

3.5 FINDING SUCCESS: STUDENT STRATEGIES

In the previous section, we identified some of the challenges that a context like our study site poses for practicing making-centered activities. In this section, we present strategies that students adopted to overcome some of the above challenges. Motivated by (Smyth et al., 2010) argument about needs assessment, we acknowledge that although the above identified challenges are potential roadblocks to practicing making-centered activities, the identified "needs" or "challenges" may not be as strongly felt by the 'maker' as perceived by researchers. Below we discuss four strategies that our participants adopted as a way to overcome *some* of the challenges (C1-C4).

3.5.1 *S1: Resilience*

Resilience, the ability to creatively cope with challenges has been discussed in the context of economically challenged settings (e.g., Olopade, 2014; Sipitakiat et al., 2004)) and makerspaces (e.g., Sheridan and Konopasky, 2016; Tanenbaum et al., 2013)). *Jugaad*, 'to make do', has been discussed in the context of India as an innovative and improvised solution to resource constraints (Rangaswamy and Densmore, 2013; Rangaswamy and Sambasivan, 2011). Within our study context, being resilient was yet again an emergent strategy. Participants creatively coped with both material unavailability (C1) as well as limited independent learning resources (C2) by being resilient.

During the workshop G2 wanted to use the force sensing resistor (FSR) and a speaker to build a project that would generate audio based on FSR input ("FSR & Sound"). However, they could not conveniently include the FSR into their prototype because they did not have a soldering iron. Once the group realized they needed – but did not have – a soldering iron, G2 reconsidered their options and decided to alter the scope of their project. This time they chose to use an LED and proposed altering the LED state based on the audio tone ("Sound Light"). The unavailability of the tool forced the participants to rethink the possibilities of what could be explored and come up with new ideas.

G1 demonstrated resilience at several levels during their after workshop experience, while building the "hello world" project (Figure 29e). First, G1 did not have a resistor that they required for their project. Instead, to keep moving forward with the project goal, P1 used their common sense to use a metal wire as a substitute for a resistor. Although the metal wire may not be the exact solution to a missing resistor, the spirit to keep trying is essential to making. Second, G1 initially built a series circuit for the "Hello world" LED display, but soon realized they did not have enough wires and had to reconsider their circuit building strategy. To overcome this challenge, G1 referenced the textbook that was provided to the school as part of the after-workshop package and found a solution to reduce the number of wires required. Lastly, P1 had forgotten how to code his circuit; instead of being deterred, he involved his friend to get programming help.

3.5.2 *S2: Nonverbal and Verbal Learning Techniques*

Nonverbal communication is a social learning technique observed in young children (Want and Harris, 2002). Lin and Shaer (2016) observed that children in their workshop in Sourth Africa, also primarily used gestures to communicate with each other. In our study, we observed imitation as a form of nonverbal communication. Within the "textbook culture", rote learning, and teacher-centric pedagogy practiced in schools in India (Kumar, 1988; Mitra, 2005; Mukherjee, 2002), imitation is an implicit learning technique. Students are trained to memorize textbook content and reproduce the same during examinations. Also, because of the teacher-centric teaching style, students are trained to follow. Therefore, over a period of time, students become accustomed to imitate or copy. While much of "textbook culture" is counterproductive to DIY culture, students adopted this learned skill of imitation as a strategy to overcome the limited learning resources challenge (C2).

On day one of the workshop, the researcher guided the participants using an introduction activity that involved building a simple LED circuit. Participants' were given time

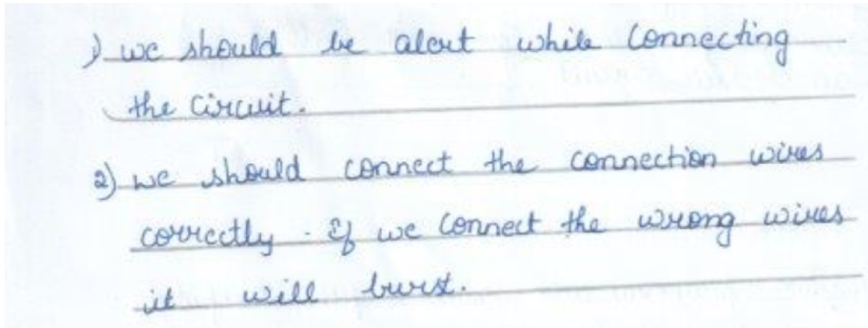
(30 minutes) to explore the electrical circuit before the workshop was continued further. During this period, G1 took the lead and connected multiple LEDs to their circuit by trial and error. Following this, four other teams (with the exception of G3) imitated them and connected multiple LEDs. This was interesting because they were not following the instructor, instead, they were following their peers. Another instance of imitation was observed during day two and three of the workshop where participants were seen visiting workspaces of other workshop group. Seeing G2 use a mini speaker in their project, G6 was also inspired and decided to include a mini speaker in their circuit. However, it is important to note that while imitation is a successful strategy to overcome the limited resources challenge, imitation as a strategy can fail if there is a problem at the source level. For example, by imitating G1's initial project proposal, four out of six groups (G1, G3, G5 and G6) proposed the "Fan" project. Because G1 was not sure about what they wanted to build for the "Fan" project, all other groups also drew a blank, as they did not know what the expected behavior of the "Fan" project should be.

In addition to nonverbal social learning techniques, asking peers or friends for help is a common verbal learning technique employed by students (Bruffee, 1984). Although students in India are mostly used to individual learning and are discouraged from consulting or interacting with their peers within a classroom setting (Mitra, 2005), within our workshop setting, asking peers for help was an emergent and encouraged strategy. With help from peers and occasionally from the researcher, students managed to build projects and stay involved in the physical computing workshop, as well as after the workshop (where there was no researcher available for help). When P6 from G2 joined G6 (due to temperature sensor burn out), participants of G6 were encouraging of their new group member and got her up to speed by explaining their circuit connections (*"red line is power, black line is ground, and white line is analog"* [P12]). They were also ready to trust their new member and willing to delegate tasks to her (*"you connect the circuit"* [P9]). We also observed that the group members would often help each other with connecting components and would think together when they were unsure. One member of the group was found to be the dominant circuit builder, while others took on the role of observers and advisers (*"connect to the positive, what you are doing is wrong"* [P12]). Similarly, for programming, since G6 was connecting multiple electronic components to their circuit, merging and debugging code was a challenging task for them. They were observed to be collaboratively dissecting code piece-by-piece to aid understanding. Seeking help of other group members was seen to be a prominent activity of G6. They were observed to validate and correct their own circuit connections by checking those of other groups (*"wait let me think, G1 has done the same"* [P12]). Similarly programming also involved inter-group collaborative effort. Participants were observed to be: (a) clarifying code logic (*"To turn off, turn the code to LOW"* [P7]), (b) clarifying syntax (*"LOW has to be in capital letters"* [P4]) and (c) suggesting possible applications for each other's projects - *"They can create a calculator (LED based) and the speaker can tell the result"* [P7].

3.5.3 *S3: Documentation and Fallbacks*

The utility of taking notes, as a way to help learning is a common practice in schools in general Howe (1974). In our preliminary observation, students took notes as the teacher dictated various aspects of computer software. In our workshop, note taking was an emergent strategy students employed to overcome limited learning resources and to create their own documentations and reference points.

Based on our analysis of the collected written notes from all the groups and the post-workshop questionnaire responses, participants documented their current experience by



1) we should be alert while connecting the circuit.
2) we should connect the connection wires correctly. If we connect the wrong wires it will burst.

Figure 31: Example of G3's written notes.

jotting down personal pointers to assist them in their future DIY attempts (Figure 31). Two other examples of personal notes are:

(1) *"a) Red line is power; b) Blue line is ground; and c) Every circuit has to end in ground line"* [P3].
(2) *"While building the electrical circuit we have to keep the pin codes in mind. After connecting the wires, we have to keep the pin codes in the mind and type in the computer"* [P11].

Unlike the elaborate notes dictated by the teacher from the textbook, the student notes from the workshop are similar in nature to logbooks in engineering and science – i.e. an informal document used for personal record keeping, to serve as a reminder of work-in-progress, recording actions and other people's input (Cetina, 2009; McAlpine et al., 2006).

As part of development of understanding (i.e. a broad view of understanding as both a process and an outcome (Gutwill et al., 2015)), note taking practices were also extended to physical circuits. Participants were observed to have a fallback circuit version they could go back to when their circuit connections were not working. A common strategy that was observed across all the working groups when their circuit connections did not work was to trace back to a simple one LED circuit, rebuild it, test it, and if found to be working, then they would attempt to reconstruct their current circuit. Having a last working version to fall back on (analogous to software versions) served both as reassurance to continue attempting to build their circuits, as well as, served as a technical base to build upon.

3.6 LESSONS LEARNED

In this section, we discuss lessons learned as researchers running a making-centered workshop within material and educational culture constraints.

3.6.1 *Engaging with the School*

We faced two primary challenges when engaging with the school. The first challenge was to gain permission to run a making-centered workshop in a school in India. We approached several public and private schools in peri-urban areas of Bengaluru, prior to running the workshop at the Kar School. Due to the non-negotiable curricula and the examination-driven structure followed by majority of the schools (Kingdon, 2007), convincing the school principal to allow students to participate in an activity that is outside their curriculum was a challenge. School principals were reluctant to let their students miss scheduled in-class learning to learn skills that were not being tested in the examinations. There were several ways we addressed such concerns. First, we had to convince the principal that learning new skills (programming, electronics) could help students in their future education and employment. Second, we had to limit the workshop hours, so that students did not miss several in-class learning hours. Third, we also learned that the school principal needed to be in control of participant recruitment. As already discussed, the principal selected students who performed academically well, as he considered them capable of coping with the break from in-class learning. The biased recruiting strategies however, can be a challenge for studies which aim to measure students' improved technology literacy.

The second challenge was our limited opportunities for continued observations. After the workshop, we donated the electronics to the school to allow students to continue exploring. One student team built a project for the school science fair after the workshop. However, from an informal interview conducted after the workshop, we gathered that students did not have free access to the electronics – the school principal had securely locked away the electronics to avoid damage and distraction during examinations. As already discussed, the poor chance of repair or replacement, discourages teachers from giving students opportunities for direct interaction (Kumar, 1988). In addition, practising skills outside of the curricula is not favoured. Because students were limited from further hands-on exploration, we as researchers had fewer opportunities for in-the-wild observations.

3.6.2 *Supporting Students*

We learned two lessons related to supporting students in India-like contexts: (a) peer-support to scaffold self-directed learning is essential, and (b) allow learners to create self-assistance structures.

In impoverished contexts, where there are limited independent learning resources and limited mentor support, we learned that peer-support to scaffold self-directed learning is essential. Learners trained in rigid educational contexts are required to work individually and are not allowed to interact with other students during class (Mitra et al., 2005). In addition, the young learners trained in rigid educational structures are accustomed to teacher-driven learning (Mitra et al., 2005; Mukherjee, 2002). However, a fundamental requirement for making-centered activities is self-direction. Alternative to the traditional, we learned that students learn self-direction if they are placed in an environment where they are somewhat forced to take ownership over the learning process (as demonstrated by the local student strategies resilience and learning techniques).

To overcome the independent learning resources challenge, we learned that learners create self-assisting learning resources to help themselves (S3). For example, learners developed informal documentation and circuit fallback plans to assist themselves in the circuit building process and, more generally, problem solving.

3.6.3 *Researcher as a Mentor*

In sharp contrast to the teacher-centric and top down schooling environment at Karlike schools, during the workshop the researcher assumed the role of a mentor. On the first day of the workshop, the mentorship role was guided by the theory of ZPD (zone of proximal development) (Vygotsky, 1987). The theory of ZPD argues that children will not learn much if they were left to discover everything on their own. The theory suggests that in the beginning the learner should be guided and assisted to help attain the necessary minimal skills. To allow students to ease into the DIY process and to encourage novice participation, methods should be employed that start simple and slowly move towards open-ended activities. For example, starting with a simple guided linear activity (e.g., making an LED blink as used in our study), will provide students an entry point to get a glimpse of what is possible. Following structured exercises, students can be given more freedom to explore possibilities and self-directed ideas. If the introduction activity is simple to follow, learners are encouraged by the initial success of completing the activity, easing the transition from the linear activity to open-ended exploration. For example, after the guided single LED blinking activity, 5 out of 6 groups experimented with connecting several more LEDs to their circuit.

We also learned that an inquiry-based approach (Alesandrini and Larson, 2002) to mentoring was helpful (especially during the 'make-a-thon'). Students at the Kar School are used to imitation. As already discussed, imitation can be harmful if the students' understanding is limited or altogether wrong (Mukherjee, 2002). However, by guiding students by asking questions, one can steer the students' towards understanding the problems and exploring alternative course of action. For example, G3 imitated G1 and proposed to build a "Fan". However, upon being asked about the expected behaviour of this project by the researcher, it was found that G3 was unaware of what the "Fan" project entailed.

3.6.4 *Maker Tools*

From our study, we learned that choice of electronics is affected by four variables: availability, transferability of skills, learning curve, and learning goals. Conventional DIY electronics like Arduino are the more viable microprocessor option for learners who may need to work with off-the-shelf components, for availability or cost reasons. Arduino-like platforms are also more accessible (the design is open-source). In a spectrum spanning transferability of skills and learning curve, Arduino-like platforms fall on one end of the spectrum (Chan et al., 2013). While Arduino has a steep learning curve, it affords learning of traditional electronics skills (e.g., breadboards, wires, components) which are highly transferable compared to self-contained educational platforms (e.g., littleBits or Makey-Makey). In addition, although Arduinos have steep learning curve, they have a "high-ceiling" (Papert and Harel, 1991), i.e. with gradual increase in learner's technical competence, the learning is extensible to explore more complex projects.

We also learned that there exists a similar trade-off for choice of programming environment: ease of access versus ability to remix code. In our study, we introduced participants to both visual programming environment, ArduBlocks, and the more traditional line programming, Arduino IDE. However, we learned that students gravitated towards using an approach that facilitated easy copy-paste and remixing of code (also observed by Kafai et al. (2014)). While visual programming is easy to approach, most starter kit books and online resources include non-visual programming sample code, making line coding a more viable option (especially in Kar-like contexts where textbooks are the main source of information).

3.7 LIMITATIONS

We conducted a short observational study of students using a single DIY platform, Arduino, in a high school in India. Our study represents one of many possible material- and educational culture-constrained settings. However, material constraints and rigid education culture exist in other developing country contexts and therefore, our design lessons learned may also apply to other communities of learners with similar constraints. We encourage future researchers to examine how our findings apply to other learner groups with similar constraints.

3.8 CONCLUSION AND FUTURE WORK

This chapter has contributed to an understanding of how students in a material-constrained and rigid educational culture context (here, a high school in India) would respond to the possibility of being involved in making-centered activities. Our study shows that material constraints can limit the kinds of projects students build, and there is a psychological cost to exploration. Educational culture can restricts student from finding the necessary intellectual courage to freely explore projects. However, even within the constraints, students were observed to be persistent and strived to overcome some of the challenges by creating local strategies. Informed by our observations, we discussed a set of lessons learned that can help other researchers interested in exploring similar contexts.

We have several directions for future work. One interesting direction is to explore how longevity of makerspaces in Kar-like contexts can be extended. Second, developing tools for supporting makers within material and education culture constraints is another important direction to pursue in the future. Lastly, from an education perspective, it will be interesting to investigate if making-centered activities could improve STEM literacy for students who otherwise receive poor quality education. We however posit that to conduct such studies, high-fidelity tools that support making within constraints have to first be put in-place.

4

ENGAGING AT-PROMISE YOUTH IN MAKER ACTIVITIES

At-risk students are generally identified with experiencing emotional or behavioral problems, which create significant barriers to learning (Kaufman and Bradbury, 1992; Eklund et al., 2009). An at-risk student is generally defined as a student who is likely to fail at school (Kaufman and Bradbury, 1992). In this context, school failure is typically seen as dropping out of school before high school graduation. It has been observed that at-risk students attend school significantly less often than students who generally succeed in school (Barrington and Hendricks, 1989). Disengagement from the educational process increases the likelihood of having poor educational outcomes (Kaufman and Bradbury, 1992) and students feel less interested in school (Cairns et al., 1989).

More recently, researchers have argued against the usage of the term "at-risk". Swadener (2012) argues that the term "at-risk" has been overused and tends to position identified students as "other[s]" in "dominant education and policy discourses" (p. 8). Such farmings also tend to systematically exclude students from many benefits of the society (Swadener, 2012). The suggested alternative is to think of them as "at promise" for success, rather than "at risk" of failure (Swadener, 2012, p. 9). We agree with this positive discourse and throughout the dissertation use the term "at-promise" instead of "at-risk".

As a way to engage at-promise youth, in this work, we explore two strategies – starter kit and open-ended activities – to introduce them to making-centered activities. We would like to point out that it is not an ability gap that separates these learners from others, but the lack of student-centered educational opportunities. Based on this, we expect similar subjective benefits for this specific group - such as, creative expression and improved self-confidence. The situational traits that hinder participation in the Maker Movement, for example, tendencies to quickly give-up, unwillingness to experiment and communicate, less engagement and lack of motivation, are more noticeable with this group (Kuznetsov et al., 2011), and thus, allow us to explore how one should introduce making-centered activities.

In the remainder of this chapter, we first discuss the motivation for this research. Next, we revisit related literature. We then discuss the methodology and the findings of our two studies (Phase 1 and 2). Finally, we conclude with lessons learned, limitations, and future work.

4.1 MOTIVATION

Maple (pseudonym) is an alternative school in Ontario, Canada, that provides educational programming for students from government approved Care, Treatment, Custody, and Correctional facilities. The students typically live in foster care or group home facilities. The primary purpose of this alternative program is to provide students with effective instruction that leads to the re-integration of students into community schools, post-secondary institutions, or employment. The students at the Maple school are identified with a variety of cognitive, behavioral, emotional and developmental exceptionalities, which included fetal alcohol syndrome, oppositional defiant disorder, various learning disabilities, anxiety, and post-traumatic stress disorder. Our overarching goal in working with this particular group of students is to explore the impact of using digital technologies on student engagement.

Based on positive results observed by some researchers such as, Kuznetsov et al. (2011) and Stager (2013), we think that introducing making-centered activities with this group was fitting. Students could continue to develop their interpersonal skills through the collaboration necessary for making-centered activities and develop their computational and analytical thinking skills through the coding and circuit activities. Furthermore, the creativity and engagement that has been witnessed in studies conducted by Buechley et al. (2007), Kuznetsov et al. (2011), and Qiu et al. (2013), motivated us to introduce the students to constructionist toolkits like the LilyPad, Makey Makey, and Arduino, in order to position them as not only programmers but designers with creative vision and agency.

4.2 RELATED LITERATURE

Kuznetsov et al. (2011) and Stager (2013) have explored the Maker Movement in the context of youth within emotional or behavioral constraints (discussed in detail in Chapter 2). We expand this body of work by contributing in the following ways: 1) we explore a larger set of constructionist toolkits (LilyPad, MaKey MaKey, and Arduino) as platforms for introducing making-centered activities. 2) Although, some of our lessons learned re-iterate findings discussed by Kuznetsov et al. (2011) and Stager (2013) i.e. unfinished projects leading to frustration, bottom-up teaching style as a useful tool for increasing participation, and benefits of casual collaboration, we found (differently) that how making-centered activities are introduced makes a difference. For example, unlike the positive acceptance of the LilyPads noted by Kuznetsov et al. (2011) for mentoring and therapy of at-promise children, our participants were less inclined or in some cases unwilling to engage in e-textile activities. Lastly, 3) our strategies also shed light on other aspects such as activity design, suggestions for considering possible entry points, and suggestions to make the process personally and educationally relevant.

4.3 PHASE 1: EXPLORING STARTER KIT ACTIVITIES TO INTRODUCE MAKING-CENTERED ACTIVITIES

In the first phase [1], we introduced students to existing starter kit activities of three constructionist toolkit platforms – LilyPad, MaKey MaKey, and Arduino Starter kit activities are a set of projects described in books included as part of the constructionist toolkits package. In this section, we begin by describing the study methodology and results of the first phase of our exploration.

4.3.1 *Study Methodology*

Our goal was introduce participants to a variety of electronics platforms and to provide participants with a practical understanding of basic circuitry and coding. We took an inquiry and constructionist approach (Magnussen et al., 2000) to teaching both circuitry and coding – students were positioned as active learners, collaborating with peers to construct knowledge and understanding of the various theoretical concepts and practical skills associated with creating circuits and computer programming. The lessons were

1 this phase of the study was conducted by Laura Morrison and Janette Hughes, co-authors of our publication for this research project (Somanath et al., 2016)

scaffolded to encourage students' engagement. The students came to the university lab once per week for a two-hour "maker" session and were allowed to work independently or with a partner. The lab manager, a research assistant, and a volunteer pre-service teacher candidate (with a background in mathematics and computer science) led the sessions. Data sources included photos, videos, and informal conversations with the students, teacher, and support worker. Data was collected during each unit for posterior qualitative analysis (Strauss and Corbin, 1990).

4.3.2 *Participants*

Eight Maple students (3 girls and 5 boys, ages 11-14) took part in Phase 1 of the study. One student was diagnosed with fetal alcohol syndrome (FAS), six students suffered from trauma (sexual, physical, and psychological abuse), two students had a diagnosis of Autism Spectrum Disorder (ASD), and two had a diagnosis of attention deficit hyperactivity disorder (ADHD). This impacted the students in one or more of the following ways: slow learning and memory problems – unable to grasp abstract concepts, and unable to remember activities that were done in class; receptive language – interrupt, talk out of context; difficulty with organization, planning and reasoning; inability to persevere with complex tasks; inability to understand cause and effect; anger control problems, aggressive behaviors; and no impulse control. All students suffered from a lack of confidence, stating frequently they were not able to do 'anything' right and felt that they were not able to be like everyone else.

Figure 32: Students working on the LilyPad start kit activities.

4.3.3 *Activities*

In Phase 1, we introduced the eight Maple students to circuitry and coding using the LilyPads (Buechley et al., 2008), MaKey MaKey (Collective and Shaw, 2012), and the Arduino Starter kits.

4.3.3.1 *LilyPad (3 classes, 6 hours)*

We first introduced participants to circuits with the LED bookmark activity in the LilyPad kits (Figure 32). We provided the participants with a brief overview of circuits and an online walkthrough of how to build a circuit using the LilyPad materials. The students were encouraged to look to their peers and online (Sew Electric website) for assistance in setting up the circuits and/or sewing. They were free to search on the Internet for inspiration and discuss their projects with peers.

Figure 33: Students working on the MaKey MaKey Starter kit activities.

4.3.3.2 *MaKey MaKey (3 classes, 6 hours)*

We then introduced the participants to the MaKey MaKey kits (Figure 33). The participants were first required to figure out the basic circuitry with the MaKey MaKey and to use some conductive object(s) in the circuits. They then used the sprite-animation and backdrop design features of Scratch (Resnick et al., 2009) to create a simple game or animation that they would eventually connect to the MaKey MaKey (with or without additional novel objects in the circuits) to use as controllers for the games.

4.3.3.3 *Arduino (4 classes, 8 hours)*

The final portion of this unit involved the introduction of the Arduino starter kits (Figure 34). The participants were given a variety of projects from the Arduino starter kit book, for example, crystal ball, zoetrope and spaceship interface. To prep the partic-

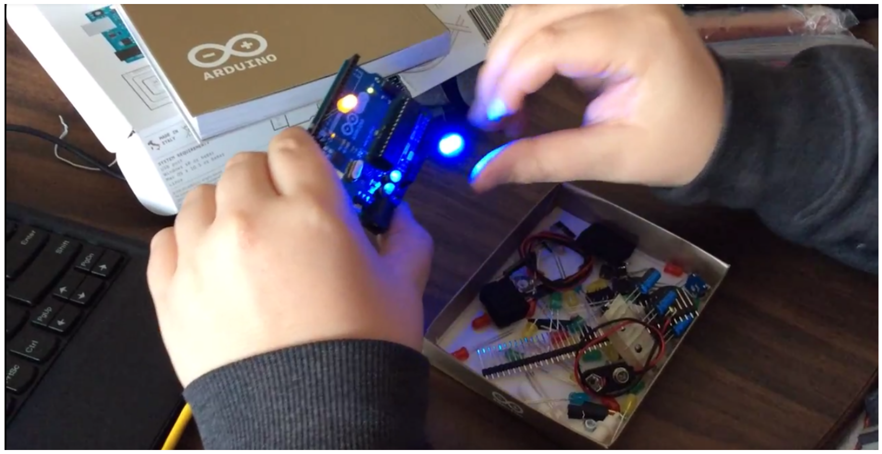


Figure 34: Student working on the Arduino start kit activities.

ipants for the more advanced coding and circuitry, we used CodeCombat website [2] to introduce students to "writing code". We also did a kinaesthetic activity with them called the Electron Run-Around. This had the students acting out the path electrons go through in various circuit scenarios.

4.3.4 *Phase 1 Results*

At the end of Phase 1 five students had attempted all of the above listed activities. However, in terms of actually completing a project, only two students were successful.

Related to the LilyPad, sewing was observed to be a time intensive activity and debugging sewed circuits was found to be quite challenging. Most students were easily frustrated, *"...LilyPads were just so boring making them... I don't want to spend that much time on them again. I had to keep sewing at the same spot cause I messed up and sew again"* [P1].

In contrast to the LilyPad, one particularly keen student had rushed through and willingly explored the MaKey MaKey kit on his own (had previously not completed the

2 https://codecombat.com/

LilyPad activity). For the remainder of this activity, he and another student took on the role of a "teacher" and guided their classmates using various online tutorials. The level of engagement and interest for all of the students was markedly higher during this activity than with the LilyPad's ("*...just plugging the chords in you can just see how everything reacts almost instantly*" [P2]). We were not sure if the increased interest was because the students now had a basic understanding of circuits, were able to program their own games using Scratch, the novelty factor that came from using items like bananas and cherry tomatoes, or all of the aforementioned.

When it came time for the students to start their work with the Arduino - coding and building basic circuits, students appeared less comfortable and less prepared to apply the knowledge gained from the previous activities. Students were frustrated as they spent a long time building circuits and programming and did not observe desired results or were caught in the loop of debugging circuits and code ("*I think the most difficult part was when I looked in the books and I'd see a project that I wanted to make and then I built all of it but some way through all that something went wrong so I had to re-do everything and it was kind of repetitive*" [P2]). Many who were not already interested in technology in general shut down (staring blankly at the components or computer screen) or chose to be engaged in other activities such as chatting with friends or surfing YouTube.

One of the most important takeaways for Phase 1 is that the students need to understand not only how to use these technologies but also understand why this knowledge is relevant to other areas of their lives. For example, the students need to be able to see that the knowledge they are constructing by learning the Arduino can help them better understand their digital world and that they can manipulate these tools per their own desires and uses. Without the ability to contextualize the work and the purpose for it the students found it difficult to maintain a level of interest necessary to work through the many challenges that are part of working with the constructionist toolkits. Lack of thorough understanding of the functionality behind the Arduino and the language used in the coding is also an obvious barrier to preventing project completion.

In terms of the tools for making, we quickly realized that constructionist toolkits had to be selected carefully based on the learning goals. For example, Arduino starter kits were not as "low-floor" (Papert and Harel, 1991) as we had considered. They required fairly proficient understanding of circuitry and programming. However, Arduino has a "high-ceiling" (Papert and Harel, 1991) – they can provide several possibilities for taking projects further. On the other hand, MaKey MaKey is simplistic, but are limited to tasks that turn everyday objects into touch interfaces. This observation highlights the need for considering balance whereby the tool enables engagement with minimal knowledge, but with gradual increase in learners' technical competence, the tool or mechanism of learning should be extensible to explore concepts that are more complex.

4.4 PHASE 2: EXPLORING OPEN-ENDED APPROACH TO INTRODUCE MAKING-CENTERED ACTIVITIES

In the second phase of our study, we explored another possible path to engaging at-promise youth in making-centered activities – open-ended projects. Phase 1 and 2 had different study goals. While Phase 1 focused on introducing participants to a variety of constructionist toolkits using starter kit activities, Phase 2 focused on exploring an open-ended, student-centered design-based approach to engaging the students in making-centered activities.

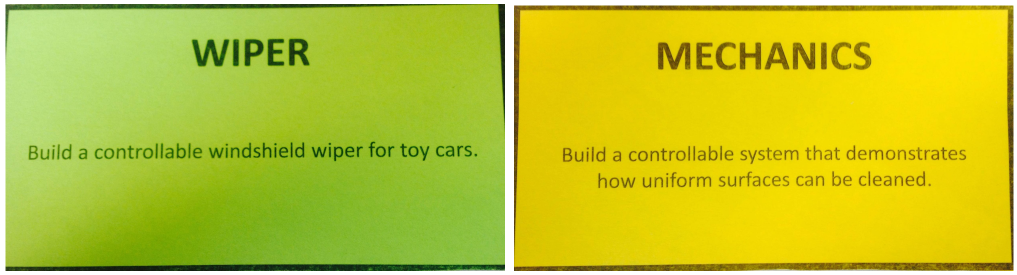


Figure 35: Example of a real world project card (left) and an abstract project card (right).

4.4.1 *Study Methodology*

In Phase 2, we simulated an experience similar to design studios (Schon, 1983), wherein the practitioner undertakes a project based 'learning by doing' approach. This also encourages development of so-called soft skills (i.e. collaboration, peer involvement, developing independence, choice making and self-determination). The designer is often given a brief or a set of requirements, following which they are expected to conceptualize and realize the final artifacts. Design studio approach encourages the designer to gain and synthesize knowledge from stages of thinking, designing, collaborating and finally creating. It is said to be enjoyable and an effective framework for critical learning (Schon, 1983).

To introduce the design studio approach, the students were cast in the role of a designer. Based on a provided design brief, students were asked to build projects in small-scale prototype forms using any material (at least one computational component) of their choice. We created two types of design briefs (*real-world activities* and *abstract activities*), and for each category, we created eight project cards (e.g., Figure 35). We provided the participants with project cards, code templates, and a variety of computational and, art and craft materials (such as switches, push buttons, LEDs, sliders, temperature sensors, mini speakers, clay, polymorph, Lego, wool, pipe cleaners, popsickle sticks etc.). The

Figure 36: Materials for building projects.

materials for making were placed in a common space for free access (Figure 36). The actuators and sensors were a mix of Phidget (Greenberg and Fitchett, 2001) and Arduino components. The electronic components were chosen such that their complexity level was relatively low for circuit connections. All the sensors had three or less pins (ground, power, analog or digital) for circuit connection.

Every student worked on an independent project, but was free to help each other. We started the workshop with a round of introductions, and briefly discussed what the participants enjoyed about programming and working with the Arduino. Next, we described all the sensors and the tangible objects students could use. Finally, we handed out the project cards to the students. Students were free to search on the Internet for inspiration to implement their project cards and were encouraged to discuss with peers or the researchers organizing the workshop.

The workshop was run over 3 days for 8 hours and was led by two research assistants and the lab manager. Similar to Phase 1, we collected field notes, photos, videos (with the exception of two students who were audio recorded), responses to questionnaires, semi-structured interviews, and informal conversations from the students and class teacher for posterior qualitative analysis (Strauss and Corbin, 1990). We also encouraged the participants to document their design process using notes and sketches.

4.4.2 *Participants*

Eight Maple students (3 girls and 5 boys, ages 12-14) took part in Phase 2. Seven out of eight students that took part in Phase 2 had previously been part of Phase 1 of the study. Six out of eight students attended on all days. Two students attended two days of the workshop.

4.4.3 *Activity Design*

We designed a set of sixteen project cards (e.g., Figure 35) to function as 'triggers' or 'scenarios' for the design brief (Schon, 1983). The students' interpretations of these cards were recorded in the form of their final projects. The descriptions for each card made explicit that the objects had to be controllable in some way and the scale of the prototype should work for tiny Lego people models (complete set of project cards included in Appendix B).

4.4.3.1 *Real-World Activities*

Real-world activities as the name suggests involved building an object that the participants would have seen or known about from their surrounding environment. The real-world activities are inspired by a type of learning activity for tangible user interfaces (TUIs), *exploratory activity* (Marshall, 2007). Exploratory activity include activities where the learner explores an existing representation or model of a topic. Our eight real-world activity cards included the following: windshield wiper, sushi table, elevator, sun blinds, swing, thermostat, bed light, and robot. physical structures and objects.

4.4.3.2 *Abstract Activities*

Abstract activities involved building an externalized representation to demonstrate an abstract concept. Abstract activities are inspired by a second type of learning activity for TUIs, *expressive activity* (Marshall, 2007). Expressive activity includes activities where the learners creates an external representation of a domain, often of their own ideas and understanding. Our eight abstract activity cards included the following: mechanics, safety, angular speed, direction control, pendulum, brightness controller, natural light regulator, and boiling point.

4.4.4 *Results*

In Phase 2, students built 13 working projects (Figures 37 and 38). Five participants built one real-world and one abstract project. Two others built one real-world project each and the remaining participant built an abstract project. The fourteenth real world

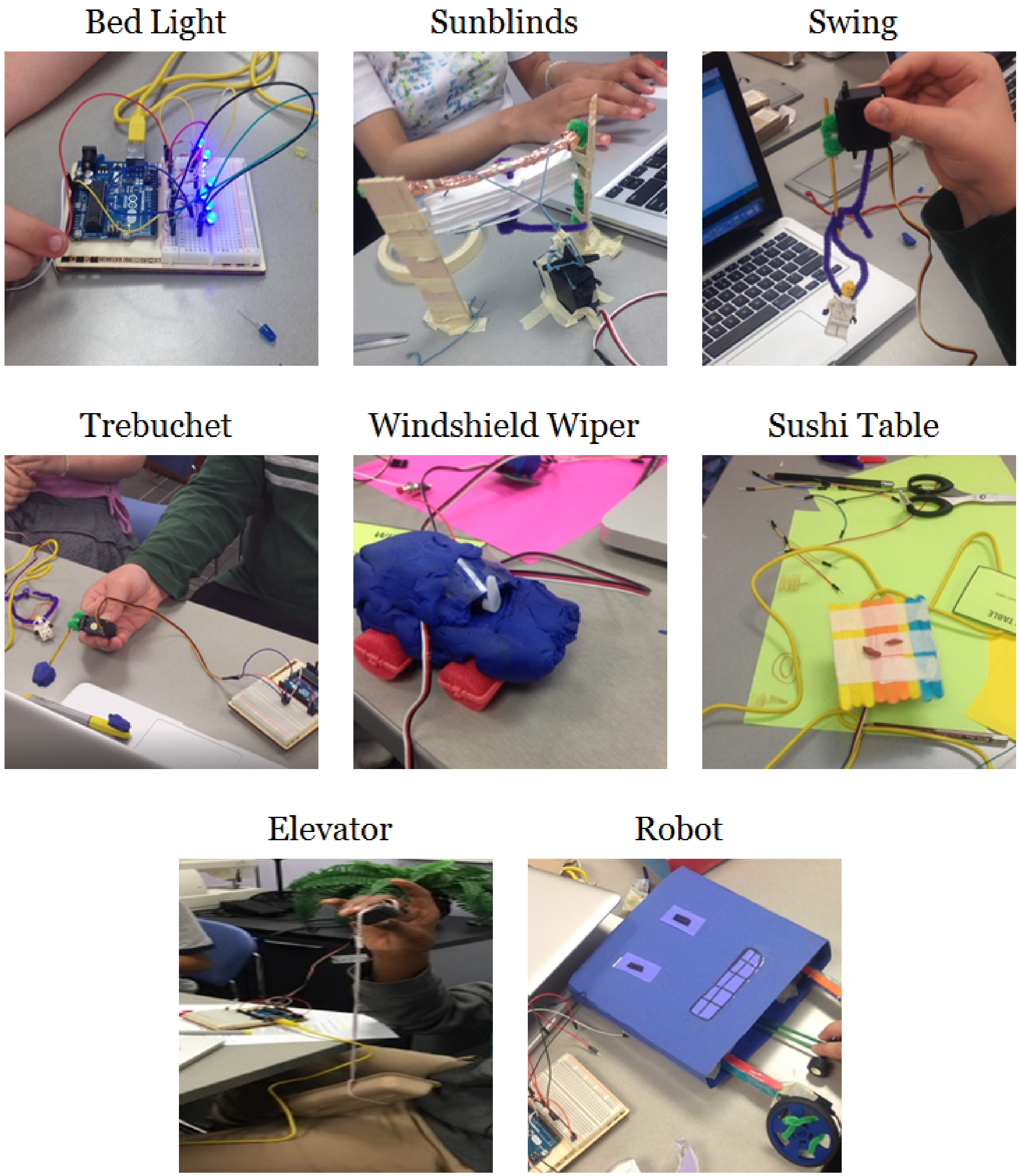


Figure 37: Students built real-world projects.

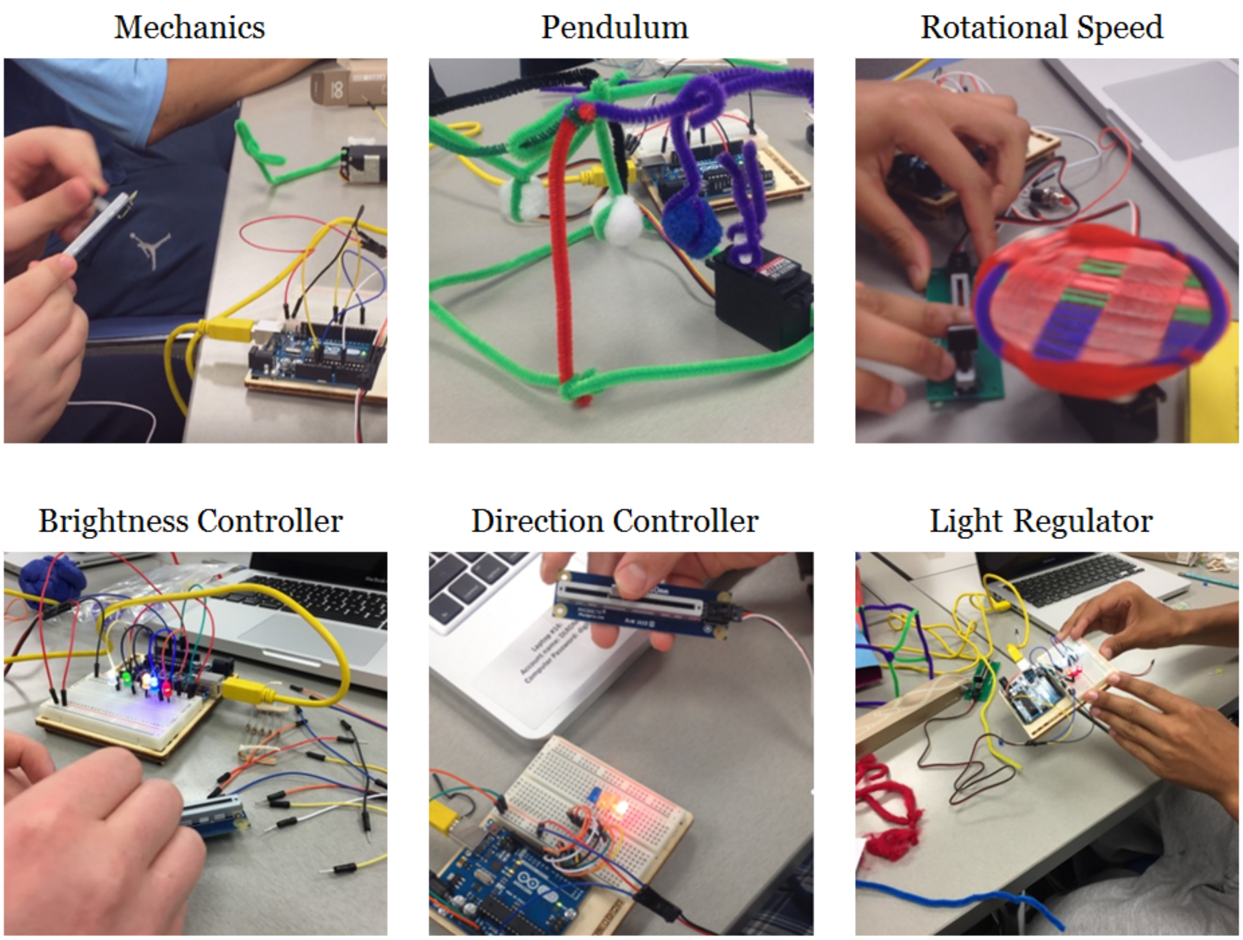


Figure 38: Students built abstract projects.

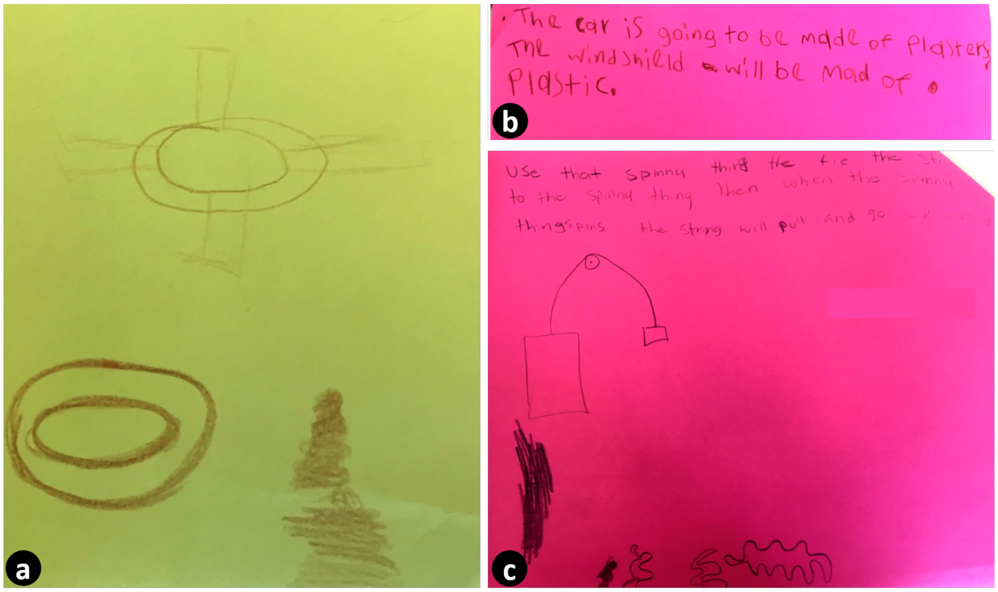


Figure 39: Student drawn sketches of real-world projects: (a) sushi table, (b) windshield wiper, and (c) elevator.

project, Robot, was physically assembled but not functional. Our observations can be summarized as below.

The way of presenting the making-centered activities (real-world and abstract) influenced the student's experience. Table 1 describes the main differences observed between the two categories of project types. In the case of real-world projects it was observed that usually participants started with a sketch or by making a list of art and craft materials needed to build the project (Figure 39). Integration of technology was mostly (5 of 7 times) the last step and was not the primary focus of the maker (technology was at the background of the building activity). For example, in the Windshield Wiper project (Figure 37), participant 6 started by making a list of materials required to build a car (Figure 39b), and then spent significant time modeling the toy car using clay, rollers and tape. The choice of integrating a servomotor to function as the wiper followed much after. Even at this point, the focus was on design and aesthetics for hiding the motor box of the servo. The participant was reluctant to modify servo template code to make sure her clay model was not disturbed. Thus, aspects of aesthetics, object design, and modeling was at the foreground of the building activity. Modeling real-world projects was also said to be relatively easier and interesting. One participant mentioned that the real-world project was easier, *"because I knew what I was making" [P8]*.

In contrast, abstract projects usually had computational materials at the forefront. The starting point for these projects was understanding how electronic components function and how they can be used. For example, in the case of Direction Controller project (Figure 38), the starting point involved choosing components to enable the functionality of direction control. Although this project was an exception, as seen in Figure 38, this project used only computational materials. Similarly, P3 who built the Mechanics project, did not sketch any ideas and said, *"I already know how I am going to build it"*, as soon as the card was handed out. Abstract projects were also said to be slightly more complex and often we saw participants spending more time building circuits and programming their components. These projects were also found to be difficult to accomplish due to programming challenges – *"I just didn't like it because I could not do any of it [programming] almost"* [P1]. One participant however, explicitly mentioned liking the complexity involved in the abstract project – *"I enjoyed it more. I liked the more complex projects"* [P6].

Three out of five participants rated liking their real-world projects more compared to the abstract projects. One participant rated liking the real-world project just as much as the abstract project. Of the three participants who built one project each, one liked the abstract project they were working on (Natural Light Regulator), one was neutral about liking their real-world project (Elevator), and one did not like their real-world Robot project (had in the start of the project mentioned robot to be the "coolest" project). This may be because students usually do not like incomplete projects (Kuznetsov et al., 2011).

Category	**Real-world activities**	**Abstract activities**
# Electronics	Less	More
# Physical materials	More	Less
Starting point	Usually started with sketches and common art supply materials.	Usually started with electronics.
Inclination	Students seemed more enthusiastic about these projects as they felt it had more design creativity. Implementation came later in the process.	Students seemed less enthusiastic about these projects because they found 'how to' implement an abstract concept more challenging.
Challenges	Students found them to be easy because the starting point is usually more common materials, and because they have a mental image of how the object looks and functions.	Students found them to be complex because: focus on functionality and high barrier to entry for computational aspects (circuitry and programming) led to frustration.

Table 1: Observed differences between the project types.

In terms of creativity, irrespective of activity type, we gathered that working with the Arduino this time around was more creative: *"We had to be creative, my entire class had to be. I had to build a swing and I had to think, what am I going to use. I used pipe cleaners and servo" [P2]*. The experience was said to be creative because: *" I liked that there was no boundaries, you could do whatever you want. Instead of using the materials the book said, I could use whatever I felt like"* [P3]. Participant P1 mentioned that they found it was *"fun"*, because, *"we had to actually do more than programming to just make lights to blink"*.

A more obvious takeaway was the benefit of employing partnered learning. It stood out as a good pedagogical tool to reduce anxiety and generate knowledge and ideas. We observed that employing this approach better prepped the students to be able to contextualize and understand the theory behind circuits as well as contextualize and understand the code they were looking at and being asked to manipulate. Think-aloud when it comes to problem solving and trouble-shooting seemed to be helpful for the students to vocalize and locate the problem and then to work through it systematically to solve it. Thinking aloud may not only have kept them accountable to the task at hand but also may have helped them better organize their thoughts and/or see the issue from a new perspective: *"I relied on my peers for input, for example, maybe you should do this...That's really good. I helped one of my classmates a lot, because she [P6] kept asking me how do the resistors work and I said I don't know..."* [P2]. The participant (P2) later mentioned having learned about how resistors work.

Table 2 shows the pre- and post-workshop responses for participants' self-assessed experiences for circuitry and programming. Columns 2 and 3 represent the number of participants who agreed (strongly agree or agree) to the asked statements. While the number of participants who felt comfortable with programming and circuitry increased

Statement	**# Agree before**	**# Agree after**
I feel comfortable programming computers on my own	2	4
I feel comfortable building electronics on my own	4	6
I enjoy programming computers	3	5
I enjoy building electronics	5	6

Table 2: Participant self-assessments.

after the workshop, most participants had to be helped with programming and circuit building.

4.5 LESSONS LEARNED

We set out to use making-centered activities as a way to engage at-promise students. In this section, we discuss a set of lessons learned that could help other researchers interested in engaging at-promise students and similar youth groups.

4.5.1 *Creativity*

Creativity demonstrated (again) its capability to become an important motivating factor when introducing making-centered activities (Giannakos and Jaccheri, 2013; Kuznetsov and Paulos, 2010; Tanenbaum et al., 2013). We saw creativity being emphasized with our group due to the students' wish to have a sense of control over the creative learning experience (explicitly mentioned by one student), a feeling which lacks in other aspects of their lives, which are heavily monitored, regulated and surveilled. Creativity, as a process defined by Csikszentmihalyi (1996), consists of five stages: preparation, incubation, insight, evaluation, and elaboration. From our experience, we learned that certain strategies can help facilitate the five stages of creativity for improving interest in making.

Preparation is about "becoming immersed, consciously or not, in a set of problematic issues that are interesting and arouse curiosity" (Csikszentmihalyi, 1996, p.5). We suggest that providing students with open-ended design briefs rather than project-specific instructions is one way to facilitate the preparation stage. Open-ended design briefs provide makers the freedom to think and realize how the project can be accomplished,. Moreover, they also have the freedom to decide which resources to use for implementing the project. A quote by the class teacher highlights that such a strategy could be helpful: *"when we did it the first time, we followed the book, and we followed the procedure laid out in the book to complete something. This time they were given a task and they were the ones who had to creatively come up with a way to program it and put it together and achieve the end result. And I think they really liked that aspect"*.

Incubation is defined as the time "during which ideas churn around below the threshold of consciousness" (Csikszentmihalyi, 1996, p.5). Incubation has no fixed duration and varies depending on the nature of the problem. We think that the studio culture implicitly prepares the students to go through this stage. Because students have to create an external representation of a textual design brief, students need time to think and implement.

Insight is gained "when the pieces of the puzzle fall together" (Csikszentmihalyi, 1996, p.5). We suggest that this stage can be facilitated by discussions with peers and teachers, and by asking students to document their ideas via sketches and notes. Kuznetsov et al.

(2011) also found brainstorming sessions to be a successful strategy to help ideation. The below conversation snippet with participant 4 (who built the Elevator project) demonstrates an example of insight gained by discussion.

> "R: *"How do you think we can build an elevator? Do you have some ideas?"*
>
> P4: *"I could hide behind it, so you guys don't see my hands, and just push it up."*
>
> R: *"...how do you think an elevator works?"*
>
> P4: *"I know it goes up and down."*
>
> R: *"So, how do we make something go up and down? If I tied a piece of string to something, how do I move it up and down?"*
>
> P4: *"You pull it?""*

After this discussion, P4 decided to search online for ideas that use servomotors to pull and release a string.

Evaluation is an emotional stage, where one decides "whether the insight is valuable and worth pursuing" (Csikszentmihalyi, 1996, p.5). While Csikszentmihalyi (1996) speaks about evaluation in terms of novelty, we think that for at-promise students, evaluation is the stage where students decide to overcome their situational traits such as, unwillingness to try, and attempt to experiment. We think this stage can be facilitated by constant positive encouragement by teachers, mentors, and perhaps peers (a strategy also discussed by Kuznetsov et al. (2011)).

Lastly, Elaboration is the stage where one validates their insights. Yet again, while in research this means conducting systematic implementation, evaluations, and identification of flaws (Csikszentmihalyi, 1996), we think that for engaging at-promise students, the elaboration stage should focus on validating ideas by encouraging students to keep trying, and acknowledge and accept that identification of flaws is part of the process (failure-positive maker mindset (Martin, 2015)). Because students get frustrated or lose interest when projects are incomplete (Kuznetsov and Paulos, 2010), we think that it is important to emphasize that failure to produce the final artifact also validates an insight.

4.5.2 *Task Classification*

The students' responses indicated that task classification had implications on what was emphasized in the learning process – creativity in design or focus on technical aspects. In real-world projects, creativity in design was more emphasized. As discussed in the results section, starting with common art supply materials as opposed to electronics, and familiarity with the real-world object (having a mental image of how it looks and functions), can promote creativity in prototyping of existing structures, followed by procedural implementation of a standard functionality. For example, the design of sunblinds can take many forms, but the function of opening and closing the blinds is somewhat standardized. This reflection is consistent with suggestions provided by Marshall (2007) for exploratory learning activity, which enable cognitive growth and reorganization of existing concepts.

On the other hand, employing abstract activities can help place more focus on improving technical skills. For example, to prototype a controllable pendulum, the maker has to explore how to implement concepts such as force, restoring force, and gravity. Since pendulums have somewhat standard design, the creativity lies in the implementation of the functionality, and in incorporating the electronics. This insight is similar to implications for expressive learning activity, which ultimately enables deeper reflection on the concepts (Marshall, 2007).

4.5.3 *Entry Point*

Learning to program and build circuits is challenging and especially for novice learners (Buechley et al., 2007; Robins et al., 2003). In our study methodology, students were shown videos of projects online as inspiration for what can be achieved using the provided constructionist toolkits. Sometimes this helped, but at other times, this external reflection was less successful. For example, in the case of the LilyPad video: *"...I put up the link to LilyPad, we started going through the other projects, some of the girls were a little more excited about doing it, but all the rest of them were done..."*[Class Teacher].

Beyond early prepping using inspirational videos, we observed that access to a wide variety of materials for making was another possible entry point. Based on students' comfort level with computation, they may choose to start with more common art supply materials (e.g., clay, pipe cleaners, popsicle sticks) as opposed to electronic materials (e.g., servomotors, sliders, touch sensor). For example, a student (P6) who was frustrated with e-textile projects, found building electronics enjoyable during the windshield wiper project. The starting point in this case was modeling the clay car (an activity the participant enjoyed), followed by incorporating the servomotor to serve as the wiper. Thus, computation was a means to an end in the creative process. In contrast, we observed that a student (P1) who was working on building a system that can clean horizontal surfaces (Mechanics project), was more enthusiastic about starting to program a servomotor. Once the servomotor was functioning as per their requirements, they attached a pipe cleaner on top of the servomotor to function as a broom.

Unlike traditional TUI's, which generally have a concrete physical interface and abstract digital representations, making-centered activities have less clear distinction in terms of what becomes the concrete and abstract representation. For example, programming was the more concrete task in the case of abstract projects, as opposed to real-world projects where the physical art supply materials were the more concrete entities. From our experience, the decision of what becomes the concrete and abstract representation is designer driven and therefore more reflective and creative. Our suggestion is to present participants with a continuum including a wide variety of entry points that embody different mixtures between the bits and bytes of programming and physical manipulatives representations.

4.5.4 *Personal Relevance*

As observed in Phase 1 of our exploration, the most important takeaway from introducing constructionist toolkits was that it was not enough for the students to simply become technology literates. From our informal discussions with the participants at the end of Phase 2, we learned that students valued the possibility of doing something that was relevant to them (whether in terms of creative skills, problem solving skills, or improving programming skills) much more than being introduced to the concept of "how-to" use electronics.

While it can be challenging to cater to every student's needs, aspects of likability, self-expression (*"I like to be creative, and this time I got a chance to be creative"*[P6]), choice making (*"instead of using the materials the book said, I could use whatever I felt like" [P3]*), potential to further improve a particular skill set (*"I think it will be cooler to do it at school - practice more programming and manipulating code..."[P7]*), and envisioning future possibilities (*"building stuff, like more electronically controlled objects" [P6]*) were few factors we observed to be relevant to the students' experiences.

Allowing students to discover the possibilities (as noted in Phase 2) as opposed to following a procedure from a starter kit book was more appealing to the students. It is surprising that although projects like LED bookmarks are equally creative and functionally relevant, students found it less engaging and useful. From our observations, we note that the process of creating can be more engaging and personally relevant if the makers are given more discoverable options. The individual tangible objects had to be presented as embodied learning materials (i.e. how can I use clay for this?; can I use servo to solve this problem? etc.) in contrast to presenting the final artifact (LED bookmark) as the embodied learning object.

4.5.5 *Relevance to Education*

Our work has a constructionist orientation and is based on the notion that learning is most effective when learners are active in making tangible objects in the real world and draw their own conclusions through experimentation with various media, where learners construct new relationships with knowledge in the process (Kafai, 2006). Unlike traditional instructionist approaches to learning (where the knowledge to be received by students is already embedded in objects delivered by teachers), constructionist learning encourages the learners to create new knowledge based on their active engagement with raw materials.

Overall, the vision of Maker Culture lends itself to constructionist learning. In our study, the participants demonstrated that students need to be given practical design challenges through the making of tangible, real-world artifacts. We were also reminded that focusing on the affordances of digital technology alone or even how the learner interacts with the technology tends to reinscribe the traditional grammar of schooling.

Instead, we need to examine entire ecologies, including the practices, material contexts, and social contexts of the students. Rather than focus on explication and step-by-step scaffolding (Rancière, 1991), our study suggests that learners should be given opportunities to begin in complexity, to discover, to explore, and to enact their own course of learning "by engaging in idiosyncratic challenges, by figuring things out, and by co-producing multimodal artefacts" (Thumlert et al., 2014, p.7). Maker Culture pedagogies engage learners in the "activity of production, enabling actors to deconstruct and reconstruct, interpret and refigure, and to make both meanings and 'things"' (Thumlert et al., 2014, p.13). Our findings suggest that the introduction of making-centered activities to education can encourage students to become designers and producers of materials and resources, and enable them to apply their experiences within various educational contexts.

4.6 Limitations

We conducted a small-scale observational study with eight students. Our study represents one of many possible youth groups within emotional or behavioral constraints. While our strategies may also apply to other communities of learners with similar constraints, future studies are required to fully validate our findings and lessons learned.

4.7 Conclusion and Future Work

In this chapter, we explored two possible approaches – starter kit activities and open-ended activities – to introduce making-centered activities to at-promise students. Based on our observations and experiences with the students, we presented a set of lessons learned that can help future researchers interested in exploring makers within emotional or behavioral constraints. Our lessons learned included suggestions for: 1) thinking about the different stages of creativity, 2) how making-centered activities could be presented to students, 3) possible entry points for making-centered activities, 4) importance of personal relevance, and 5) relevance to education.

In the future, there are several directions to explore. While we explored how activities can be presented to such makers at an empirical level, applying these lessons learned to technology design is yet to be explored. Our short-term study highlighted that making-centered activities can engage at-promise youth in technological practices. In the future, it can be interesting to conduct long-term studies to observe if making-centered activities can help students sustain interest in educational activities and serve as a means of self-help.

5

MAKING DESPITE MATERIAL CONSTRAINTS WITH AUGMENTED REALITY-MEDIATED PROTOTYPING

As part of many making-centered workshops, people build physical computing projects such as toys, robots, e-textile projects, and utilitarian products using constructionist toolkits (e.g., Buechley et al., 2008; Qiu et al., 2013; Kafai et al., 2014; Peppler et al., 2016; Somanath et al., 2017). However, such making-centered activities are only available to those with access to materials for making (Bean and Rosner, 2014).

Material cost or accessibility concerns present potential roadblocks to building physical computing projects (Sipitakiat et al., 2004; Somanath et al., 2017). When electronic components are not available, makers may be forced to conduct iterative on-line or empirical research to find alternatives (Sipitakiat et al., 2004). However, not all makers have independent learning resources (e.g., the Internet) to conduct such research (Somanath et al., 2017). Some makers may become discouraged and discard their original project ideas entirely (Somanath et al., 2017). This inequity compromises the democratic vision of the Maker Movement (Tanenbaum et al., 2013); by helping people continue to make despite missing material resources, we can equitably extend the reach of the Maker Movement's vision.

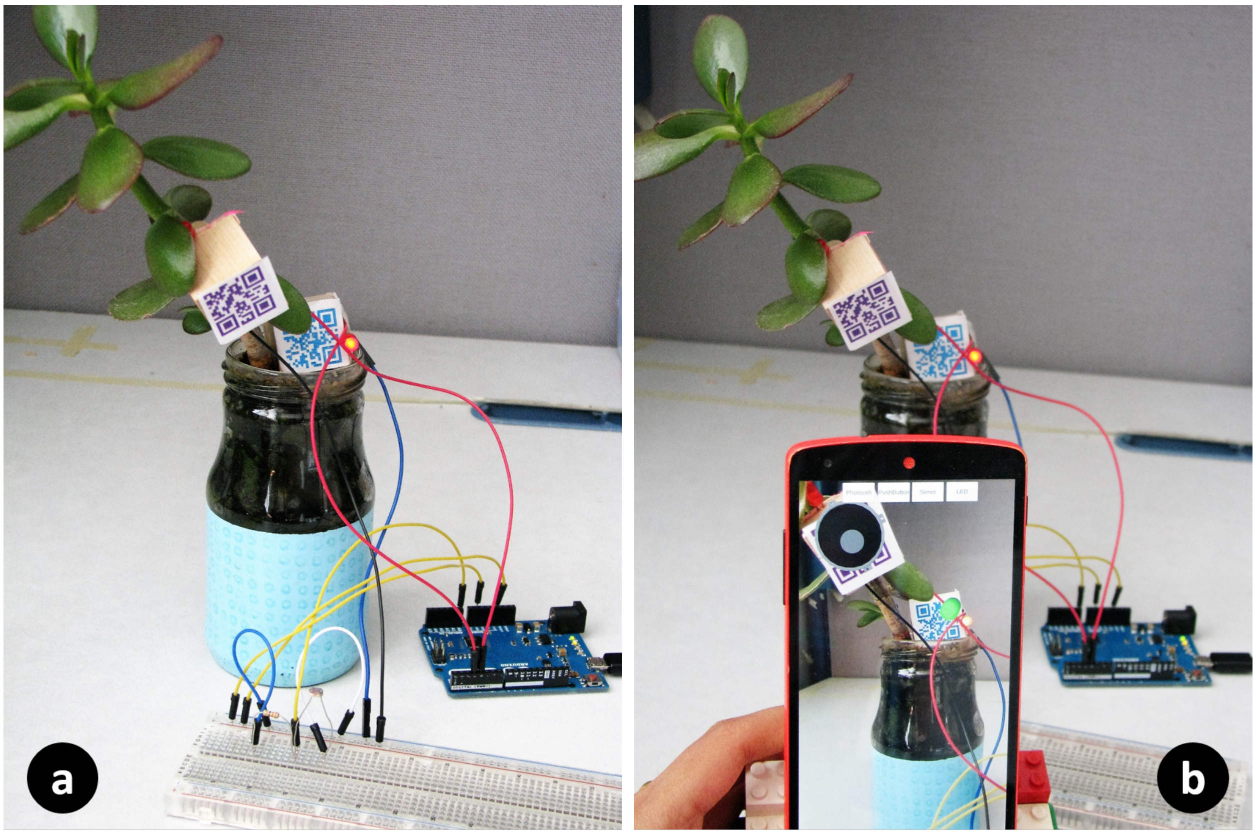


Figure 40: AR-Mediated Prototyping blends real and virtual components to create physical computing projects despite missing materials. Above, a plant monitoring system prototyped using our technology probe (Polymorphic Cube).

One possible response to missing materials is to digitally create and simulate physical circuits. Researchers have proposed electronics simulation software (e.g., Circuits, 2017) as a way for makers to virtually explore "what-if" scenarios easily and instantly when no electronic components are available. However, this undermines the essence of building physical projects – physical computing embraces the physicality of electronic components, circuitry, and interactions (O'Sullivan and Igoe, 2004). Alternatively, we propose pursuing an intermediary between purely virtual and purely physical representations of the project (Figure 40). *How might we blend a virtual simulation of missing components with real-world physical prototyping materials?*

Augmented Reality (AR) is one way to blend virtual simulation and physical prototyping materials by superimposing computer-generated digital content on a real world object (Milgram et al., 1995). In this chapter, we propose *AR-mediated prototyping* – an approach to prototyping physical computing projects with both real and virtual electronic components. Our goal is for makers to leverage AR to continue to build as much as possible until missing electronic components become available.

In this remainder of this chapter, we first briefly revisit related literature. We then present our vision for designing technology for *AR-mediated prototyping*. Next, we discuss the design and implementation of a technology probe, *Polymorphic Cube* (PMC) based on our vision. Then, we describe two studies that capture makers' reactions to our technology probe and the broader vision of AR-mediated prototyping. Finally, we conclude with lessons learned about how AR-mediated prototyping allows physical computing projects to continue despite material constraints.

5.1 RELATED LITERATURE

The concept of using AR-mediated prototyping to address material constraints for making is new. Polymorphic Cube (PMC), a technology probe for prototyping physical circuits using real-world and virtual electronic components, represents a first exploration of an AR-mediated prototyping tool for making within material constraints. However, PMC is inspired by several prototyping tools (Hartmann et al., 2006) and AR-based educational tools (AR circuits, 2016; Conradi et al., 2011; Asgar et al., 2011; Chan et al., 2013; Narumi et al., 2015; Uhling, Frank, 2016) previously discussed in Chapter 2.

The PMC prototype is inspired by d.tools (Hartmann et al., 2006) and the tabletop systems (Conradi et al., 2011; Uhling, Frank, 2016), which demonstrate the ability to blend physical prototyping materials with virtual information. However, our goal is different from these systems – we want to help makers continue to build their physical projects despite missing electronic components. In addition, unlike these systems, the PMC system works with real circuits and simulates the missing I/O components in situ. The simulated I/O components not only respond to on-screen interaction triggers (as in d.tools (Hartmann et al., 2006)), but are physically and functionally part of the circuit.

Like previously demonstrated AR-based tools for electronics, PMC design also uses AR to blend the physical circuit with the simulated I/O components. However, the goal of AR in PMC is *not* to teach electronics (AR circuits, 2016; Chan et al., 2013), or to enhance the circuit building activity (Narumi et al., 2015) and the design process (Weichel et al., 2014). We use AR to simulate missing I/O components so that makers can continue building physical interactive circuits.

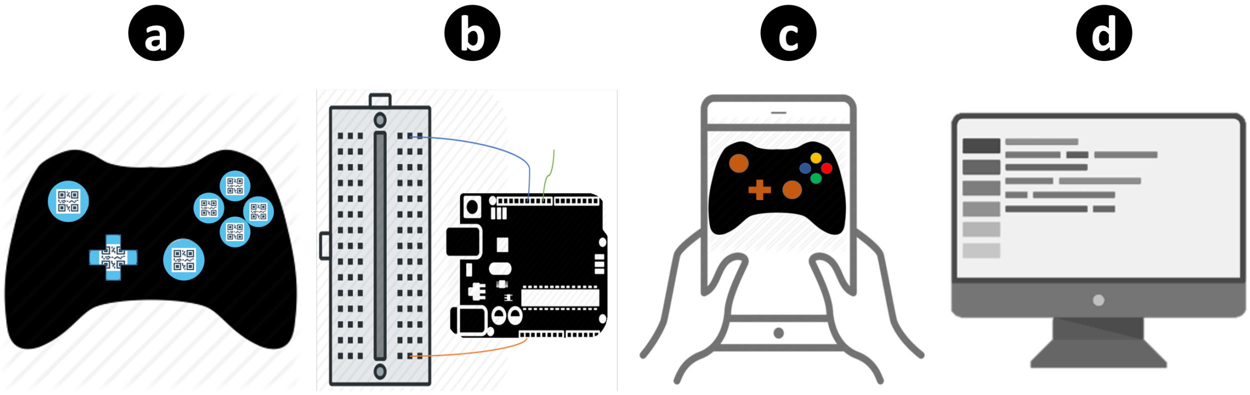


Figure 41: Parts of technology for AR-Mediated Prototyping: (a) trackable placeholder object, (b) programmable microcontroller and circuit, (c) companion AR application, and (d) programming IDE.

5.2 AR-MEDIATED PROTOTYPING: VISION

AR-mediated prototyping lets makers substitute virtual stand-in components for missing electronics. Makers connect components to, interact with, and program a unified circuit that includes both real-world and virtual materials (Figure 40).

Our vision for designing technology for AR-mediated prototyping consists of four parts (Figure 41): (a) a trackable physical placeholder object (e.g., a game conroller-like object as shown in Figure 41a), (b) a programmable microcontroller (e.g., Arduino as shown in Figure 41b), (c) a companion AR application (Figure 41c), and (d) a programming IDE (Figure 41d). To build circuits the maker connects the physical placeholder object to a microcontroller pin. The maker uses the companion AR application to assign the placeholder object to a selected missing electronic component (e.g., LED, servo, photocell). Makers can program both connected AR components and real-world components in the same microcontroller-specific programming language.

Within this base vision for AR-mediated prototyping, there are several aspects to consider: (1) physical and virtual form of AR components, (2) circuitry and programming, (3) physical interactions, and (4) social interactions. In this section, we discuss these aspects and suggest four goals for designing technology for AR-mediated prototyping. We also present three possible high-level tasks that AR-mediated prototyping can support based on the four aspects and the goals for technology.

5.2.1 *Physical and Virtual Form*

Unlike real components, AR components are linked in both physical and virtual space. In our vision, makers choose the dimensions and physical appearance of the placeholder object; this could be a physical replica of the missing component, any readily-available found object, or even an enclosure for the final circuit. For example, Figure 41a shows the use of a game controller-like object as a placeholder object. Because the placeholder object is maker-defined, the AR tags that link physical and virtual representations need to accommodate different shapes and sizes, and readily attach to a variety of placeholder materials. For example, Figure 41a shows the use of circular and cross shaped AR tags.

We envision that makers assign a placeholder object to a virtual electronic component, represented in virtual space by a 3D model. The AR component may represent a single electronic component, or a more complex subcircuit. The AR component can represent components that are either analog or digital, and either input or output. AR components should also simulate physical behaviors of electronic components, such rotation speed of a motor, or motion of actuated sliders via appropriate animations. Based on these considerations, we suggest that the technology for AR-mediated prototyping should help makers easily build (construct and assign) AR components (*Goal #1*).

5.2.2 *Circuitry and Programming*

Physical computing projects require both physical circuit building and microcontroller programming. We envision that AR-mediated prototyping should build on skills that makers have learned from using existing physical computing kits. For example, while some physical computing kits require traditional circuit-building skills using breadboard and wires (e.g., Arudino), others are more plug-and-play (e.g., Phidgets, LittleBits). We envision that makers will connect AR components to the circuit in the same manner as real-world components connect to the maker's preferred microcontroller platform. The microcontroller then detects both the real and the AR components that are connected to the circuit.

Makers program microcontrollers to build interactivity into physical computing projects. We envision that makers will program AR components in the same programming language and code base that defines the behavior of real-world components. This allows the hybrid ecosystem of real and virtual components to behave as a single system.

Based on these considerations, technology for AR-mediated prototyping should enable coupling – via circuity and programming – the AR components and real-world prototyping materials to create a unified project (*Goal* #2).

5.2.3 *Physical Interactions*

In physical computing projects, people physically interact with the electronic components. In the case of AR-mediated prototyping, people need to simultaneously interact with AR and real-world components. Possible ways of interacting with AR components will depend on the AR technology being used.

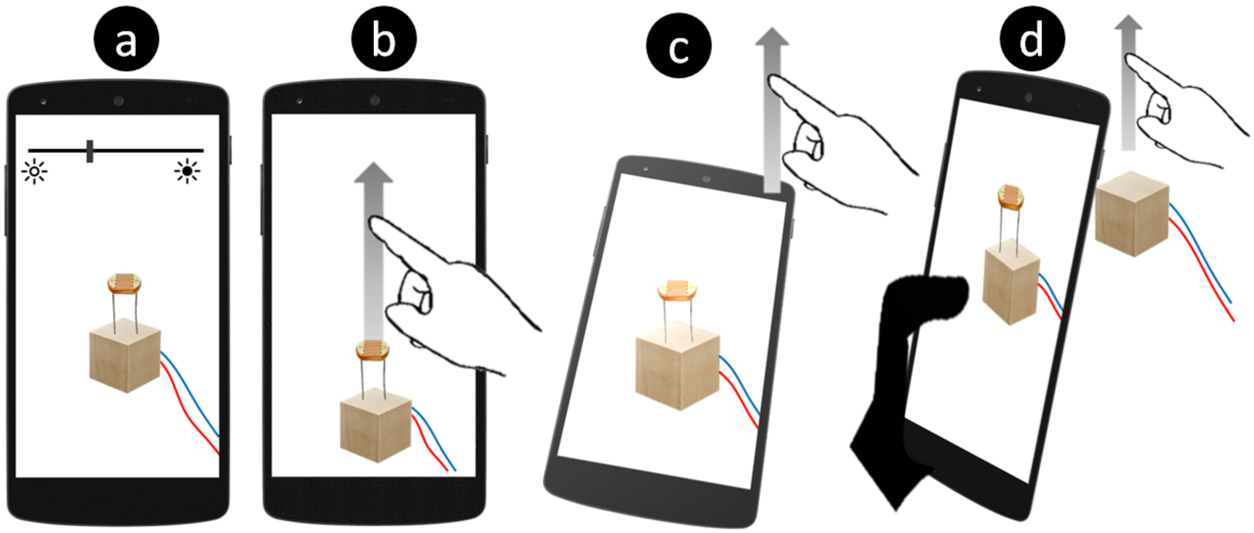


Figure 42: Interacting with AR light sensor component using (a) on-screen widget, (b) touch, (c) built-in phone sensors, and (d) physical placeholder object.

For example, for AR-mediated prototyping using mobile devices such as smartphones or tablets, we identified four possible interaction styles (Figure 42), based on a continuum of AR interaction paradigms (Dubois12 et al., 1999).

First, the maker could use an *on-screen widget* (Figure 42a), e.g., controlling the direction and position of a servomotor using an on-screen widget. Second, the maker could use *touch interactions* (Figure 42b), e.g., pressing a button by tapping its virtual representation on a capacitive touchscreen. Third, a maker could interact with *built in phone sensors* (Figure 42c), e.g., changing the volume of a virtual mini speaker by using the volume controller buttons on the side of the phone. Fourth, a maker could interact with the *physical placeholder object* (Figure 42d), e.g., controlling a rotation sensor by physically rotating the placeholder object. Alternative AR platforms (e.g., Hololens) may be able to use some of these interaction styles, but may also introduce additional ways of interacting with AR components. Based on this consideration, technology for AR-mediated prototyping should support appropriate interaction with AR components (*Goal #3*).

5.2.4 *Social Interactions*

Materials also play a social role in online and real-world makerspaces, as makers share electronic components, as well as its corresponding software code or project documentation (Burke, 2014). Traditionally, people share physical electronic components separately from software code. However, with AR-mediated prototyping we envision that makers can assign an AR component and its corresponding software code to a single AR-tag. Makers can share the AR tag physically in co-located settings, or post online for others to download. Based on this consideration, technology for AR-mediated prototyping should support sharing both components and code as a single unit (*Goal #4*).

5.2.5 *Possible Tasks*

We envision people might use the AR-mediated prototyping tool for three types of tasks. These tasks serve as a starting point to explore the different aspects of building a physical computing project, and are not meant to be an exhaustive list of possibilities. In this section, we present our suggested list of possible tasks and a walk-through of the steps required to accomplish the tasks.

- Task #1. Experiment with a variety of components: To test design ideas, makers iteratively assign an AR component to different electronic components. For this task the maker first constructs an AR component by attaching an AR tag to a physical placeholder object, and then, assigns the AR component to electronic component(s) using the companion application. This task can be primarily supported by technology that allows makers to easily build AR components (Goal #1).

- Task #2. Prepare for transitioning to real-world components: To build a high-fidelity system makers switch the AR components to real-world components. This could happen after a prototype idea is finalized and/or when the components become available. As part of this task, first the maker builds a physical circuit by connecting both the real-world and AR electronic components. Second, the maker writes code to program the circuit. Third, the maker tests the circuit by interacting with the electronic components. Lastly, maker swaps the AR components with the real-world components. This task can be primarily supported by technology that allows makers to couple AR components and real-world prototyping materials (Goal #2), and test the circuit by interacting with the components (Goal #3).

- Task #3. Share components and code: To work on projects in a social setting, makers collaborate with others and share electronic components and software code. As part of this task, the maker saves the electronic component(s) and software code in a specific AR tag. In co-located settings the maker then hands out this AR tag to others. For remote sharing, the maker uploads the AR tag and shares a link to download. This task be supported by technology that enables sharing of AR tags mapped to specific code and components (Goal #4).

5.3 POLYMORPHIC CUBE: TECHNOLOGY PROBE

We implemented a technology probe (Hutchinson et al., 2003), Polymorphic Cube (PMC) [1] based on our vision for AR-mediated prototyping. The goal of PMC is to elicit feedback from makers about AR-mediated prototyping. To that end, PMC is simple and currently

1 A video demonstrating PMC can be accessed at: https://drive.google.com/open?id=0B4RuX8NmbsLDOTlxOWFXcEVRcWs

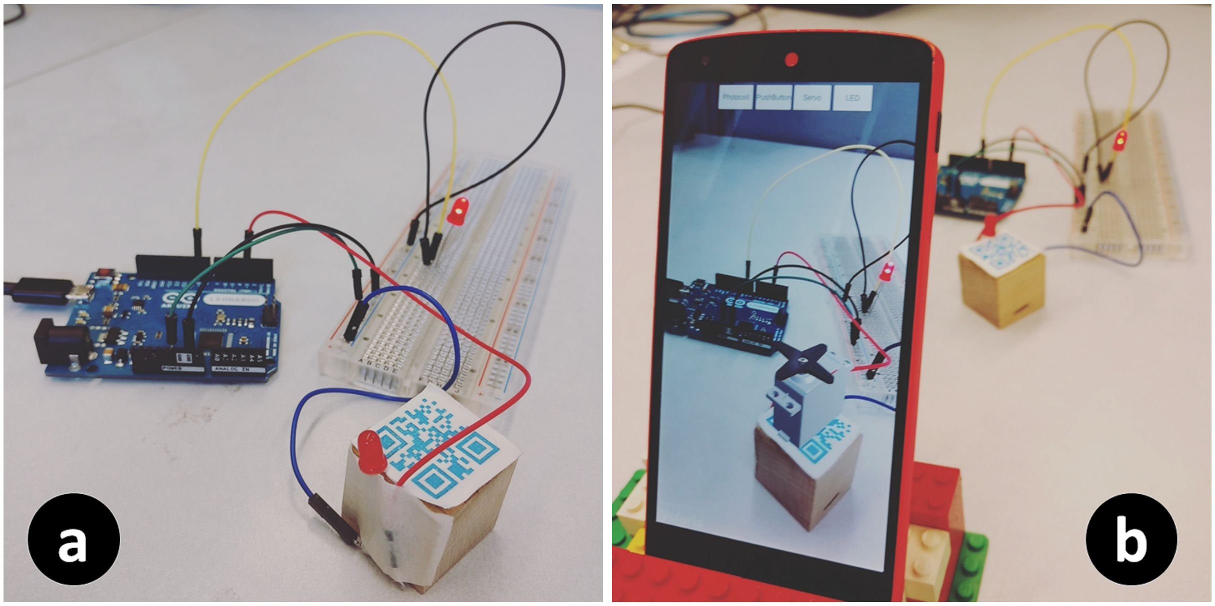


Figure 43: Polymorphic Cube: (a) trackable wooden cube connected to the Arduino and (b) companion AR application.

allows people to assign AR components, build and program circuits, and interact with the AR components (topics previously discussed in our vision).

5.3.1 *Design Overview*

PMC consists of two main parts: a low-fidelity trackable physical cube (Figure 43a) and a companion smartphone AR application (Figure 43b). The cube, a physical placeholder for the missing electronic component, can be physically connected to a microcontroller pin (here, an Arduino), to facilitate building a physical circuit. The companion AR application allows the maker to select and assign PMC to the missing electronic component (e.g., LED, servo, photocell). Makers can program the connected AR components and real components using the Arduino IDE.

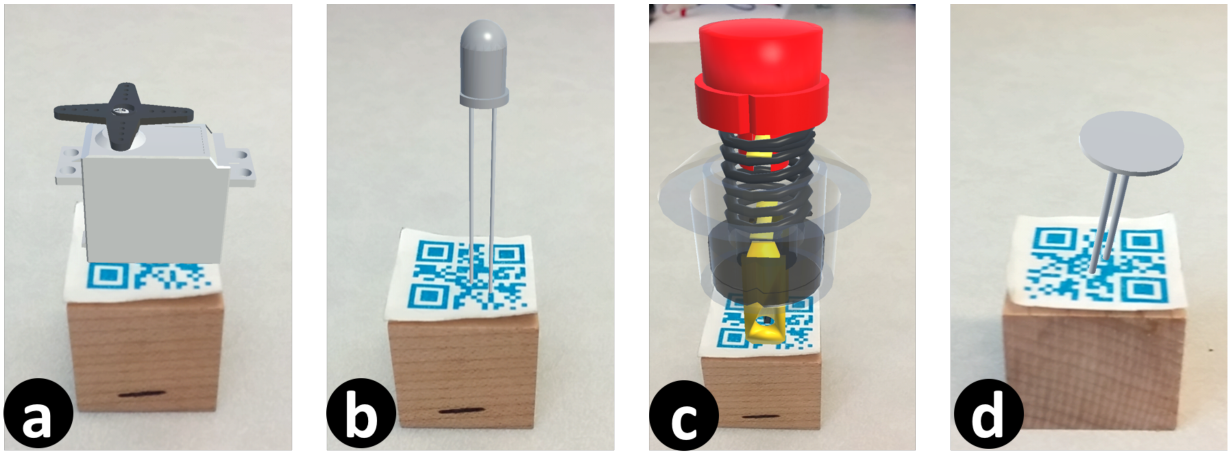


Figure 44: PMC prototype currently includes four electronic components: (a) servomotor, (b) LED, (c) pushbutton, and (d) photocell.

5.3.1.1 *Construct and Assign AR Components*

PMC is a very simple low-fidelity prototype – a wooden cube with a QR code and LED attached with tape (Figure 43a). The cube is a durable and a stable placeholder to connect to a circuit. We use a one-inch cube for consistent tag recognition. While our PMC is simple, the use of at hand materials such as paper-based AR tags, a found placeholder object, and a low-cost electronic component, to build an AR component means other people can build their own PMCs within material constraints.

A companion mobile application allows the maker to assign the cube to a variety of components (Figure 43b). Currently, PMC can simulate four components (Figure 44): LED (digital output), servo (analog/digital output), pushbutton (digital input), and photocell (analog input). The maker can select and assign the cube to different I/O components through a button-based menu at the top of the mobile interface. We use the concept of polymorphism to assign the cube to a variety of electronics. For visual interface design, polymorphism is said to be an essential property for keeping an interface simple (Beaudouin-Lafon and Mackay, 2000). Our current prototype achieves polymorphism by enabling the maker to author the stand-in component. Rather than having a large set of pre-assigned QR codes assigned to different I/O components, the maker can assign a QR code to any I/O component they need.

5.3.1.2 *Build Circuit and Write Code*

One face of the cube has an LED with two wires soldered to the LED legs. The wires connect the cube to an Arduino pin (Figure 43a). Connecting a component using wires is analogous to connecting traditional electronics. The simplistic two-wire connection reminds the maker that a component has to be connected to a specific microcontroller pin to program the component just as with using real components. The LED also serves as a feedback mechanism, indicating to the maker that the cube was connected correctly – if the wires are correctly connected to the Arduino, the LED turns on. To program the AR components, the maker uses Arduino serial commands.

5.3.1.3 *Test Circuit*

PMC implements direct touch-based interaction with the virtual I/O components (Figure 42b). Direct touch with the virtual I/O components mimics interaction metaphors that a maker would use to interact with real components, thereby taking advantage of learned hands-on skills (Ishii and Ullmer, 1997). Each AR component model resembles the form of real component and affords similar interactions as the real components. For example, for a push button, the maker can push the cap of the 3D button model using touch on the screen. To visualize a button press, the button spring is animated to compress and expand.

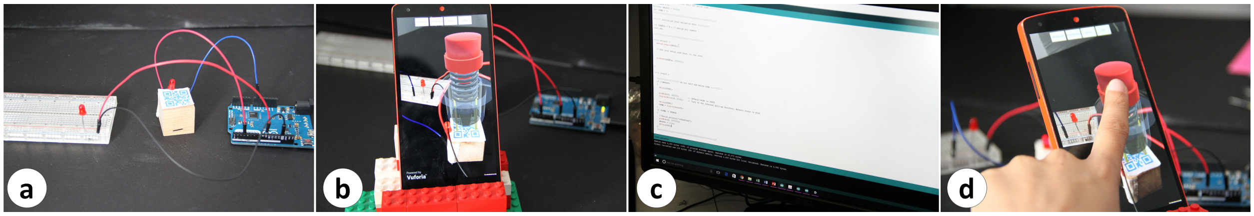


Figure 45: Example of a simple light controller built using PMC: (a) build a circuit, (b) assign the PMC cube to a pushbutton, (c) write code, and (d) interact with the AR pushbutton to test the system.

5.3.2 *Example*

Figure 45 demonstrates an example of using PMC to build a simple prototoype of a light controller system. In this example, PMC simulates a missing pushbutton. A maker completes four steps to prototype. First, the maker builds a light switch circuit (Figure 45a). For this, the maker connects the PMC cube to the breadboard and the microcontroller using the two wires attached to the cube. Second, the maker assigns the PMC cube to a pushbutton (Figure 45b) by selecting from the button-based menu positioned at the top of the screen. Third, the maker writes code to control the real-world LED using a virtual button and uploads the Arduino program to the Arduino Leonardo via USB (Figure 45c). Lastly, the maker interacts with the simulated pushbutton on the mobile screen by pressing and releasing the button cap to turn the light on/off (Figure 45d).

5.3.3 *Implementation*

Implementation of the PMC prototype system includes the following two main parts:

5.3.3.1 *Hardware*

PMC hardware has the same circuit footprint as an LED. Therefore, the microcontroller can detect the AR component. Our current implementation, does not use a smart breadboard to analyze the entire circuit. As a result, electrically, real-world components do not effect the AR components. However, because the microcontroller can detect the AR component, their behavior can be effected by the real-world components via programming. We configure a specific digital pin to be the PMC cube pin (as shown in the code snippet below).

```
int state = 1;
boolean detect = false;
int temp = 1;

void loop() {
 if (!detect)
  {
    delay(1000);

    // default mode is INPUT
    pinMode(3, INPUT);
    // Turn on the internal pull-up resistor
    digitalWrite(3, HIGH);

    delay(1000);
    temp = digitalRead(3);
  }
```

```
  if (temp != state)
  {
    // AR component connected to pin 3
    pinMode(3, OUTPUT);
    detect = true;
    delay(100);
  }
}
```

5.3.3.2 *Software*

All of the AR electronic component models used we downloaded free from the 3D warehouse website [2]. We used the Vuforia unity SDK [3] to create the Android AR application. We wrote a C# program to establish communication between the Arduino and the companion smartphone application. The C# program communicates with the Arduino via a serial port. The communication with the Android application is via Wi-Fi.

The maker programs the behavior of the entire circuit, both AR and real-world components, using the Arduino IDE. To simulate an output AR component (e.g., servo), the C# program gathers the state value of the component (e.g., servo's position) from the Arduino code in real-time and writes them to a file on the webserver. The values written to the file are then used to simulate the AR component (e.g., rotate the servo). Similarly, for an input component (e.g., pushbutton), the C# program gets values via on-screen phone interaction ('0' for press down and '1' for release) and communicates that to the Arduino.

2 https://3dwarehouse.sketchup.com/?hl=en
3 https://developer.vuforia.com/downloads/sdk

The code snippet below shows the Arduino code used to turn on/off a physical LED via a simulated pushbutton.

```
if (Serial.available() > 0)
    {
      // reading from the serial port.
      ch = Serial.read();
      if (ch == '1')
      {
        // button is pressed, LED on
        digitalWrite(ledPin, HIGH);
      }
      if (ch == '0')
      {
        // button is not pressed, LED off
        digitalWrite(ledPin, LOW);
      }
    }
```

5.4 EVALUATING AR-MEDIATED PROTOTYPING

We conducted two studies, an observational lab study and an online questionnaire-based study, to evaluate PMC and to elicit feedback on the broader vision of AR-mediated prototyping. As part of the lab study, participants were introduced to PMC and they built simple prototypes of a controllable lamp using real-world prototyping materials and an AR component. We gathered feedback about usability and usefulness of PMC and the benefits and limitations of the broader vision of AR-mediated prototyping for addressing material constraints. Next, in the questionnaire-based study, we specifically focused on understanding how people envision interacting with AR components. In this section, we first detail the observational lab study method, followed by a description of the questionnaire-based study method. We present the results of both our studies in the next section.

5.4.1 *Observational Lab Study Method*

The primary goal of this study was to observe if participants are able to build physical computing projects using a single AR component.

5.4.1.1 *Participants*

Twelve people from the ages of 20 to 44 (3 females, 9 males) participated in our study. We recruited via notices posted to local makerspaces, emails sent to university wide graduate student mailing list, and word-of-mouth recruitment. We recruited participants who had prior experience with building circuits using the Arduino and Arduino programming. We selected participants on a first-come first-serve basis and the participants were remunerated with $20. Our participants self-identified as makers and came from different disciplines and professional backgrounds: energy teacher, IT/ electronics consultant, visual artist and science communicator, and graduate students (electrical engineering, computational media design and computer science). Participants had a range of self-rated expertise in physical computing: novice (1), beginner (5), competent (5) and expert (1). Participants also had varied frequency of involvement with physical computing activities: rarely (4), occasionally (3) and frequently (5).

5.4.1.2 *Experimental Setup*

We conducted the study at a desk with a PC connected to dual displays and used one portion of the desk as the activity area. We taped an Arduino Leonardo to the activity area of the desk. In addition, we provided the participants with a breadboard, several connection wires, a polymorphic cube, a Google Nexus 5 smartphone, a LEGO-based phone stand, and circuit diagram printouts. We placed the real electronic components used for the study – 1 LED, 1 servo, 1 photocell and 1 pushbutton on another desk beside the participants' desk. The circuit diagram printouts corresponded to each of the four components used in the study. We pre-installed the PMC application on the smartphone used in the study. For the purpose of this study, the participant could assign the PMC cube to a virtual LED, servo, photocell, and pushbutton. We provided sample code for all of the components. To help participants copy and paste code, we displayed the Arduino IDE on one monitor and the sample code on the second monitor. We placed a HD camera overlooking the activity area to video record all of the sessions. The researcher sat next to the participants' table to observe and to take notes of participants' interaction experience.

5.4.1.3 *Procedure*

We ran participants through the study individually, with each session running for about an hour. We introduced each participant to the goal of the study and encouraged them to talk-aloud throughout the study, expressing their thoughts about PMC. The study consisted of the following parts:

Pre-study questionnaire: Each participant completed a pre-study questionnaire that asked personal demographic information and a few questions regarding physical computing (i.e. prior experience, frequency of involvement, and things they had previously built).

In addition, the questionnaire asked two questions about how participants addressed the challenge of missing electronic components during electronics prototyping.

Familiarization phase: After participants filled out the pre-study questionnaire, we conducted a step-by-step demonstration of building a pushbutton controlled servo circuit. For the demonstration, we used a physical pushbutton and the AR component was the servo. We first walked-through circuit building. After circuit building, we demonstrated programming. We copy-pasted the appropriate code samples into the Arduino IDE and uploaded the code to the Arduino board. Finally, we demonstrated the working system.

Task phase: After the familiarization phase, the participant was involved in the task phase. For this study, the goal of the task phase was to build a controllable lamp (a modified version of the Arduino *Touchy-Feely Lamp*[4] starter kit activity) using an LED (output), servo (output), photocell (input) and a pushbutton (input).The task phase consisted of two parts:

(A) Sketch phase: In this phase, we asked the participants to sketch four unique designs of a controllable lamp. The participants used a task sheet to illustrate their ideas. Because the task was to build a controllable lamp, the use of an LED was consistent across all the designs. To create the scenario of "a missing component" we took each sketch and selected one component to be an AR component. We indicated each AR component used in each trial to the participant using purple text as shown in Figure 46.

(B) Building phase: After the sketch phase, the participants built each design one at a time (total 4 trials). For each trial, the participant was always required to simulate one missing I/O component using PMC. There was no time limit for the trials. When the prototype was working as proposed in the design, the participants did a quick demo of the system for the researcher and then moved to the next trial.

4 https://www.youtube.com/watch?v=AtplYQKyB5A

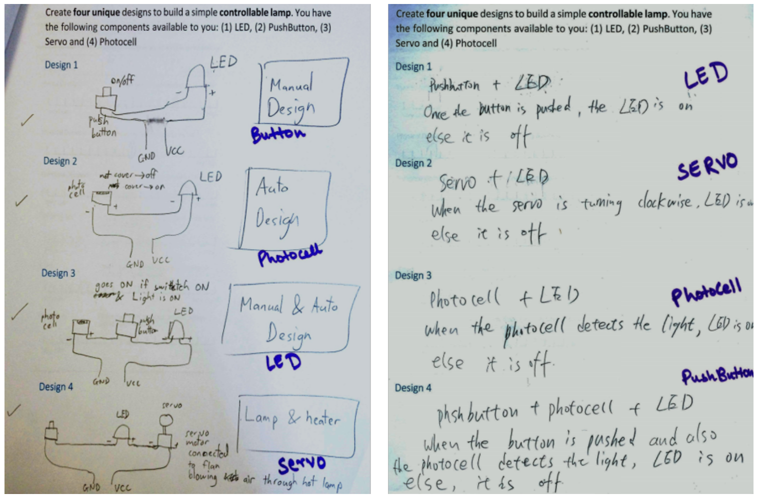


Figure 46: Example task sheets

Post-study questionnaire: At the end of the task phase, we asked participants to fill out a post-study questionnaire about their overall thoughts on using the PMC. We asked them to rate PMC using a 5-point Likert-scale (Likert, 1932) (where 1 was much worse and 5 was much better) on questions related to ease of use and experience with different components.

Post-study interview: The study concluded with a semi-structured interview intended to explore aspects of AR-mediated prototyping such as design iterations, multiple PMCs, and sharing.

5.4.1.4 *Data Analysis*

We transcribed individual interviews for posterior qualitative analysis Strauss and Corbin (1990). From responses to each interview question, we made a list of higher level-themes (e.g., easy access and flexibility, interactivity supports sharing) as related to each of our design goals. We quantitatively analyzed the Likert-scale questionnaire to compute the median values. We used the individual video recordings to identify and count the different interaction styles used by the participants when interacting with the AR object.

5.4.2 *Questionnaire Study*

The primary goal of this study was to learn about how people prefer to interact with AR components (Goal #3). This study was conducted after the lab study.

5.4.2.1 *Participants and Procedure*

We asked our pilot participants and participants from our first lab study to take part in the online questionnaire. Thirteen participants responded.

We asked the participants to fill out an online questionnaire comparing the four different interaction styles for AR-mediated prototyping (shown in Figure 42). The questionnaire asked participants to rank the four interaction styles in order of preference (where 1 was least preferred and 4 was most preferred). We also asked participants to provide a rationale for their ranking order. The questionnaire consisted of eight categories of electronics: (1) light sensors, (2) weather sensors, (3) flex, force and vibration sensor, (4) direction sensors, (5) distance sensors, (6) sound sensors, (7) biometric sensors and (8) encoders. The categories are based on existing classification of electronics on online electronics store such as SparkFun and Phidgets. We analyzed the questionnaire quantitatively to compute the mean values. We qualitatively analyzed the participants comments to understand their rationale.

5.5 RESULTS

In this section, we discuss results from both our studies in the light of our goals and tasks of AR-mediated prototyping.

5.5.1 *Responding to Lack of Materials*

The meta-level goal for AR-mediated prototyping is to help makers' overcome the lack of material resources (e.g., electronic components). Although our motivation for addressing lack of electronics comes from more extreme resource-constrained contexts such as, an impoverished school in Brazil (Sipitakiat et al., 2004) and India (Somanath et al., 2017), we found lack of materials to be a potential roadblock even when participants had easy access to material resources.

From our pre-study questionnaire, we found 11 of 12 participants living in North America had previously encountered a situation when they had limited access to electronics. Overall, participants had three practical solutions to overcome the challenge of material unavailability. First, the majority of our participants (8 of 12) had placed an order online and had decided to wait while the electronics arrived:"*Usually I stop what I am doing and order the component. This can be difficult as it can delay the project for weeks sometimes*" [P8]. Second, a few participants (4 of 12) had attempted to re-use existing and readily available electronics as an alternative:"*I missed some switches in my design which I ended up replacing with transistors and resistors combined*" [P7]. Lastly, one participant mentioned that they had borrowed the missing electronic components from a friend.

Using PMC, all participants agreed that they could continue to build projects despite missing components. Overall, all participants found that PMC is easy to understand (median=4, n=12) and was usable for the given task (median=4, n=12). Four participant quotes explicitly highlight the usefulness of PMC in responding to a lack of materials:

> "*if I open my box at home I have all of these [button and LED], but I don't have a servo. So it was cool that we started with the servo, because I actually tried what I could have done at home. Because I did not have a servo, I simulated it and it was really helpful*" [P1].

> "*sometimes you want to try a part, but you have to order it. By the time it gets shipped, you may have forgotten the idea or had different ideas. It would be awesome if it could be as easy as going to DigiKey and download a model and play with it using this [PMC]*" [P6].

> "*an alternative path to something like this would be a complete simulation but, this is more fun then watching on the computer. So I think this is a brilliant idea!*" [P5].

> "*could save a lot of money by not having to buy all the different components you would need for design*" [P8].

5.5.2 *Building with AR Components (Goal #1, Task #1)*

In our vision, we suggested that technology for AR-mediated prototyping should allow makers to build AR components (Goal #1) and this in turn can help makers with experimenting with a variety of components (Task #1). In this section, we discuss participant feedback related to this goal and task.

We envisioned that both physical and virtual forms of an AR component are important. From our lab study 4 of 12 participants suggested that physical form of an AR component is less important. Participant P4 argued that in AR-mediated prototyping, components do *"not need to have a lot of physical presence"*. Participant P4's rationale was that because AR components are virtual we do not have to worry about the physical space they occupy – *"one does not have to worry about things like if a motor has place to spin"*. Participant P4 suggested that the placeholder objects could be small discs or even a cable. A similar opinion was expressed by participant P10, who mentioned that when used in prototyping, the placeholder object could be shrunk, reduced to pieces of paper, or *"even integrated into the breadboard, so the breadboard would have specific pins that were cubes"*. Participant P12 added that if a placeholder object were used then *"it would be nice to have the cube comparable to the real component size"*.

Specific to virtual form, in our implementation, we used realistic 3D models of electronic components. Participants P6 and P9 specifically mentioned that the ability to have a 360 degree view of 3D models made the experience feel physical. One participant however, suggested that *"maybe it would be interesting to choose to go more abstract, because you can't really go fully realistic"*[P12].

In our current PMC design, we treat each AR component as a single electronic component (1-to-1 assignment). While seven participants agreed with this view, five participants suggested assigning one placeholder object to multiple components or sub circuit. Participant P3 suggested that when using multiple AR components the circuit could become *"bulky"*. Therefore, to *"cut the space"* they suggested that it might be better to assign a single placeholder object to multiple components. Participants P11 and P13 mentioned that 1-to-many assigning could be beneficial when the placeholder object represents multiple instances of the same components (e.g., array of LEDs). One participant specifically mentioned that assigning one placeholder object to multiple components could be useful to better facilitate interactions with the components: *"Let's say, we had a big circuit here and* *we had 5 cubes spread. Then maybe at some point I would like to turn on a switch and cover a photocell, and press another button. So I don't know how to deal with it"* [P7].

Specific to experimentation with components, overall, all participants found PMC easy to assign and experiment with different components: *"I liked being able to change to anything very easily. That was the main thing I liked about it [PMC]"* [P12]. All our participants also mentioned that they could imagine using a tool like PMC to test their design ideas if the tool included access to a large library of electronic components. Participant P13 specifically mentioned that such a library need not be limited to existing electronic components and should include end-user defined components.

5.5.3 *Coupling AR and Real-World Components (Goal #2)*

We suggested that technology for AR-mediated prototyping must should allow makers to build a unified circuit by coupling the AR and real-world components via circuitry and programming. In this section, we discuss feedback related to both circuitry and programming.

All participants successfully built four unique prototypes of the controllable lamp using PMC during the lab study. Overall, we found that participants with varying expertise level found it easy to build circuits using PMC (median=4, n=12). Participants could easily connect the cube to their circuits using the two wires attached to the cube.

From post-study interviews, we learned that 4 of 12 participants liked the simplistic two-wire connection. Participants P10 and P11 mentioned that the two-wire connection was easy and had an advantage over complex real components which require more knowledge and effort when (re)building a circuit. Participant P9 mentioned that simple wiring also helps aesthetics – *"its kind of cleaner"*. Although the goal of our vision is to support prototyping within material constraints, participant P1 considered PMC also to be a useful educational tool. They suggested that for educational applications it might be important to support wiring setup similar to real components: "*Let's say we had a transistor which is a three pin, then you may have mislead that it was only a two pin connection*" [P1]. In our current implementation, participants do not need to add resistors for the virtual components. Participant P11 explicitly mentioned that not worrying about details like resistors helps makes prototyping sometimes easier. As a suggestion for improvement, participant P1 mentioned, *"In general this [PMC] looks pretty good. Maybe in the software you can have some design rule check, for example connected to a node"*.

Related to programming, we found that participants with varying expertise level found it easy to program the AR components using the Arduino IDE (median = 4, n=12). Participant P12 explicitly mentioned that AR-mediated prototyping is helpful for: "*prototyping code; to see if it would do what you wanted, especially when you have complex code and want to see if your output would work correction*" [P12]. Unlike our vision that suggested leveraging makers learned skills with current physical computing platforms, one participant suggested using a tangible programming approach to AR-mediated prototyping:"*if there was a way to get rid of programming, then it [AR-mediated prototyping] would be even more physical*" [P9]. Participant P9 suggested using an approach similar to the technique of program by example demonstrated in projects such as Curlybot (Frei et al., 2000) and Topobo (Raffle et al., 2004).

5.5.4 *Interaction with AR components (Goal #3)*

In our vision, we considered four interaction styles. In PMC, we implemented touch-based interactions with the AR objects (Figure 42b). To understand how people generally

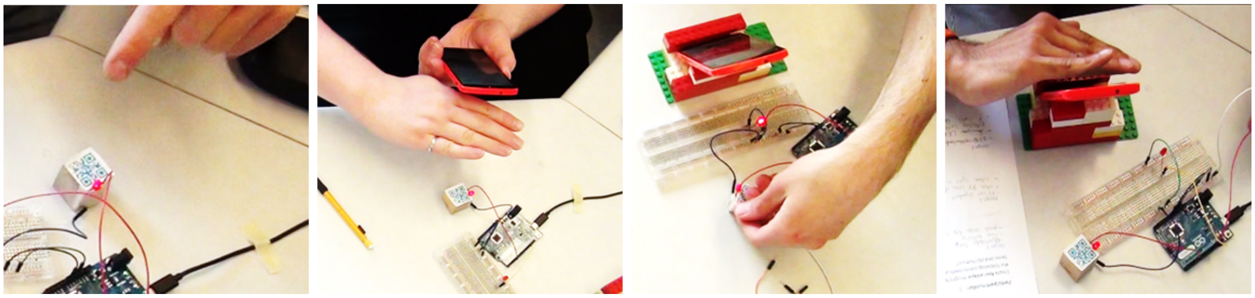


Figure 47: Observed examples of participants attempting to interact with the physical placeholder object and built in phone sensors.

prefer to interact with AR components we looked to our study data from both the lab study and the questionnaire-data.

During the lamp-building task in the lab study (first study), we observed that 7 out of 12 participants attempted to interact with the simulated I/O components using built in phone sensors and direct interactions with the physical placeholder object (Figure 47). However, in contrast post-study responses from the lab study highlighted that participants liked the touch-based interactions.

Responses to the the Likert-questionnaire from the lab study revealed that participants found interacting with a virtual servo, photocell, and pushbutton using touch about the same as interacting with their real-world counterparts (median=3, n=12). Specifically for input components, post-study interviews revealed that all participants liked the simple touch-based interactions. Participant P9 explicitly mentioned that the animation of physical components provided useful feedback for interaction:"*With the physical one [button], it was like did I get it, did I press it on. With this [virtual button] I knew it was working, the feedback was really nice*" [P9].

This pattern was also observed in the responses to online-questionnaire study, which included a wider variety of electronic components (sensors and encoders). The responses to the online questionnaire showed that in order of preference, the majority of the participants first preferred either touch-based interaction with the virtual component or interactions using widgets (median=2.5, n=13), a close second choice was built in phone sensors (median=2.25, n=13), and direct physical interaction with the placeholder object was least preferred (median=1.94, n=13).

Participants reasoned that they preferred touch-based interaction with the virtual components because it is intuitive, the interaction was collocated with the object, it facilitated more control, and that it could be consistently used with a variety of electronics. Interacting with widgets was preferred because participants had prior experience using widgets for controlling specific values.

Although interaction using built in phone sensors was a close second choice, all participants commented that because phones had limited sensors, this interaction style would be less consistent. One participant added: "*this seem like a tricky option because it can create a disconnect between how users interact with components. If I'm acting within a virtual world for one component (say a button), it doesn't seem consistent that the phone acts as a sensor for another (why do I have to shake the phone for a vibration sensor/accelerometer?)*" [P13].

Similarly, a reduced degree of coherence (i.e. the degree to which physical and digital might be perceived as the same thing) (Koleva et al., 2003) was highlighted as a possible problem for interacting directly with the placeholder object: "*I feel like its more appropriate for a full virtual reality environment. In the current AR setting, it seems like it would divide your attention between two objects (the AR device, and the actual circuit). I prefer focusing on one thing at a time, so it makes sense to me to keep all interactions virtual*" [P13].

5.5.5 *Social Interactions (Goal #4, Task #3)*

We did not implement a function to share code and components in our current version of the PMC. However, our participants reflected on this aspect during the interview. We gathered that the participants envisioned two types of sharing: sharing software code, and sharing software code and electronics.

In the *Sharing Software Code* model of sharing, participants (5 of 12) suggested that every individual maker could own a personal placeholder object, but the software code mapped to the placeholder object could be shared as a community resource. Some of the suggested benefits of this approach included sharing code in classroom settings (P6), and the ability to download models of electronics and use code written by others to support implementation tinkering (P8, P12). In addition, this model was said to work well for remote collaborative practices (P12).

In the *Sharing Software Code and Electronics* model of sharing, participants (5 of 12) suggested that the maker could share the placeholder object as a single unit comprising code and component. Some of the suggested benefits of this approach included: allowing makers to get quick help from experts (P4, P5), encouraging open-source sharing of code (P7, P13), and enabling exchange of complex physical systems such as a tangible puzzle game, with others (P13).

5.5.6 *Transition to Real-World Components (Task #2)*

In our lab study, design refinement took the form of rebuilding four unique versions of a controllable lamp. We did not explicitly focus on transitioning to real-world components. However, in each trial participants had to swap out AR components with real components. Two participants (P10, P12) explicitly mentioned that transitioning between AR components was easy: "*It [PMC] was used in different situations. It [PMC] did not have to be reconfigured. Only programming had to be changed. So physically it is definitely an advantage over the physical components*" [P10].

Participant P5 added, that PMC-like tools are useful during the *"experimentation and playful phase"*. However, they suggested that after the prototyping phase is complete and when making actual designs, the maker has to use a variety of tools for making:"*this [PMC] is another useful tool and you would use it along with all the other tools*" [P5].

5.6 Discussion and Future Work

The primary goal of our AR-mediated prototyping approach is to enable makers to use technology to continue building physical computing projects despite missing material resources. All our participants' could overcome the lack of a required I/O component and build several prototypes of the controllable lamp using PMC. Initial reactions of makers toward PMC have been encouraging. Participant statements not only reveal that our vision considerations were meaningful, but they also demonstrate a high level of excitement toward the use of PMC-like technology for making when challenged with material shortages. However, PMC, as a first exploration in this direction, also raises some questions to be explored in the future.

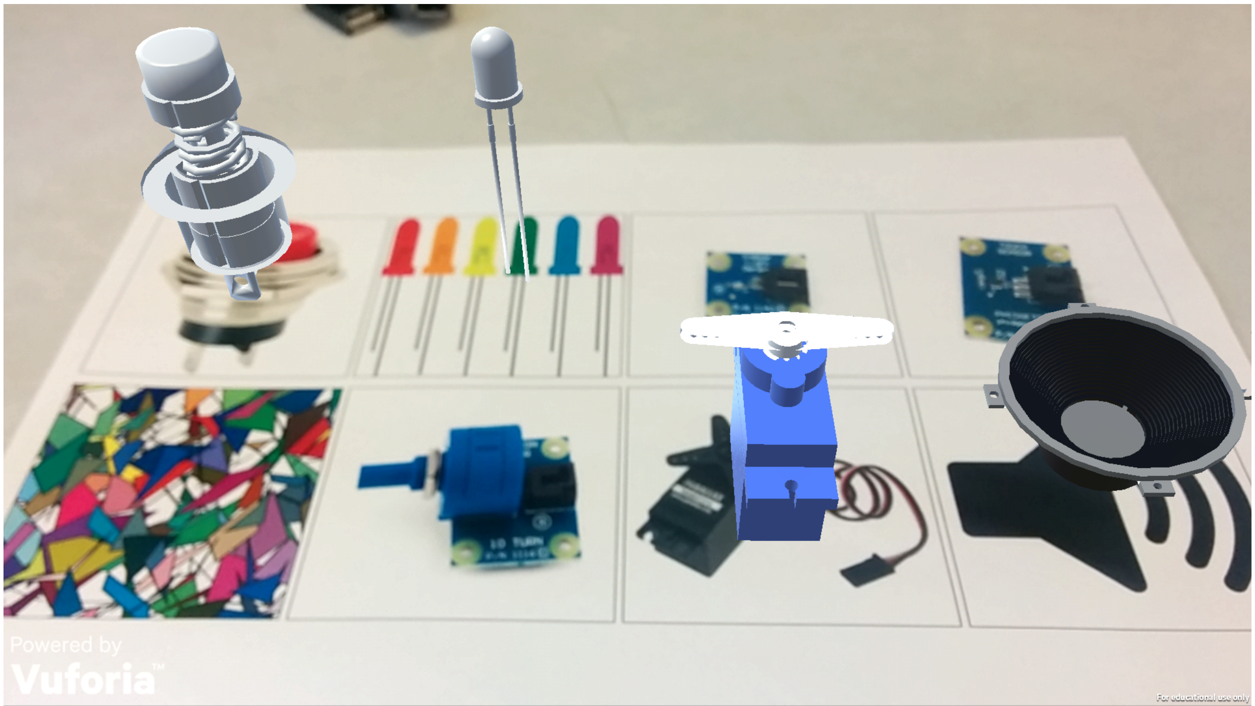


Figure 48: Detecting multiple AR components.

5.6.1 *Physical Kinematics*

Participants found PMC useful for overcoming material lack, prototyping physical computing ideas, fearlessly exploring electronics, and sharing code and electronics. However, one limitation of our current implementation of PMC is that AR components cannot physically demonstrate material behaviors. In the future, it would be interesting to explore the use of low-cost self-actuated flexible interfaces (e.g., Roudaut et al., 2013) to enable physical kinematics.

5.6.2 *Scalability*

In our current study of PMC, we allowed participants to use one cube as a stand-in for one missing electronic component. Our findings indicate that participants could successfully work with one augmented cube when building physical circuits. However, in scenarios where a maker may not have immediate or easy access to many materials, scalability of the technology is important. From an implementation standpoint, we have successfully tested tracking multiple objects (Figure 48). However, as indicated by our participants, there are several aspects to consider to scale interaction when using multiple AR objects. For example, if two placeholder objects are placed far away from each other and the maker needs to interact with them simultaneously, then the maker would need a much larger display than a phone can offer. One solution is to make use of larger displays. It would also be interesting to explore solutions similar to Surround-See (Yang et al., 2013) that enable peripheral vision around mobile devices. In addition to exploring how to scale AR-mediated prototyping, an important thread to explore in the future is understanding how many AR components can be used in circuit before AR-mediated prototyping begins to deviate away from physical making.

5.6.3 *Open-source 3D models*

Our participants appreciated the flexibility of AR-mediated prototyping. All participants mentioned that having an elaborate list of virtual components would improve the usefulness of PMC-like tools – *"...I see myself using it [PMC] if you had a library of models"* [P5]. In our current PMC prototype, we used freely available online 3D models of electronics. Digital easy-to-use maker tools for creating models of electronic components would help expand the ecology of virtual materials that makers can use within their hybrid AR-mediated physical computing projects. For example, participant P13 suggested that support for design iteration could be improved further by allowing participants to use both physical and virtual components (e.g., virtual knobs, screens, and UI components). In addition, makers could share their digital design files along with software code on online communities such as Thingiverse [5] or Instructables (Wilhelm and Griffith, 2015) to help others explore ideas by tinkering code and material functionality.

5.6.4 *Transferability of Skills*

Interviews with participants raised questions about skill transfer. One participant mentioned that the simplistic two-wire connection can be misleading and it might be initially difficult to understand the abstraction of the cube. To enable transferability of skills, PMC could use AR to provide information about missing physical materials. Similar to works like LightUp (Chan et al., 2013) and ConductAR (Narumi et al., 2015), when makers replace the surrogate AR component with a real component, the AR application can help makers with building circuits, optimize circuits and also help find errors and correct errors. This could help makers overcome both material challenges as well as conceptual difficulties involved in technology-based DIY.

5.6.5 *Interactions with Virtual Components.*

Likert-questionnaire responses revealed that there was no clear majority for the preferred interaction style. For example, while majority (10 of 12) of the participants said that

5 http://www.thingiverse.com/

the touch-based interaction (Figure 42b) with a pushbutton felt the same as real-world interaction with a pushbutton, 5 of 12 participants found touch-based interaction less satisfying for the photocell. We used touch-based interaction technique in the current PMC to provide a consistent interaction metaphor. In the future, it would be interesting to explore which AR technique is best for different categories of components (sensors, actuators, and encoders).

5.7 CONCLUSION

In this chapter, we presented our vision for technology for AR-mediated prototyping for physical computing projects. The goal of AR-mediated prototyping is to help makers continue to build physical computing projects despite missing material resources. To demonstrate and evaluate our vision we implemented a technology probe, Polymorphic Cube (PMC). The goal of PMC was to provoke thoughts about making despite missing electronics, and to elicit feedback about PMC in the light of our vision. We conducted two studies to gather participants' reflections about AR-mediated prototyping. We found PMC could help makers focus on prototyping project ideas instead of researching for alternative materials. In addition, makers can continue to take part in implementation tinkering and testing of multiple design ideas. One limitation of our hybrid AR-mediated prototyping is that the AR components are virtual and cannot physically affect real components. However, participants' reaction highlights that this might be a negligible limitation given that makers can continue to prototype rather than discard or forget ideas while waiting for components to become available. We encourage future researchers to examine how our findings and design goals apply to other instances of technology for AR-mediated prototyping.

6

OVERALL DISCUSSION

In this chapter, we discuss the two high-level themes of this dissertation research: constraints and technology for making. Our discussions draw from both our observational studies (Kar School study discussed in Chapter 3 and Maple School study discussed in Chapter 4) and design explorations (AR-mediated prototyping and Polymorphic Cubes discussed in Chapter 5).

6.1 CHARACTERISTICS OF CONSTRAINTS

In this section, we describe what we think are the three characteristics of constraints for making, based on our experiences so far.

6.1.1 *Tangible and Intangible Constraints*

The first characteristic of constraints for making lies within its inherent tangible and intangible nature. To explain this characteristic, we draw parallels from the Goldratt's Theory of Constraints (TOC) for manufacturing (Dettmer, 1997). TOC is a methodology for identifying the most important limiting factor (i.e. constraint) that stands in the way of achieving a goal (here, making), and systematically addressing the constraint to achieve the goal.

Based on TOC, a *tangible constraint* for making is one where the cause is measurable or observable and the effect may be directly measurable or observable. For example, lack of material resources is a tangible constraint. The cause, "Amy does not have electronic components", resulting in the effect, "Amy did not build a project", are both observable.

An *intangible constraint* is one where the cause is not directly measurable or observable and the effect may be directly measurable or observable. For example, an emotional constraint is difficult to measure or directly observe, unless the person states that they have a specific problem (e.g., dislike a specific tool). However, an effect caused by emotional difficulty such as not engaging in maker-centered activities may be directly observable.

From a methodology and technology standpoint, identifying and addressing tangible constraints is more straightforward than intangible constraints. Because we know the cause and effect for tangible constraints, we can develop specific interventions and test if the final goal is achieved. For example, to address a lack of electronic components, one straightforward design implication is to find ways to allow makers to continue to build projects as much as possible using other available real-world components (Sipitakiat et al., 2004).

In contrast, identifying and addressing intangible constraints is challenging because the cause is unclear. For example, because it is difficult to clearly identify what emotional difficulties limit at-promise youth from getting involved in making-centered activities, often researchers employ a variety of strategies to explore aspects of engagement, motivation, or others. In addition to our own research with at-promise youth, we observe such exploratory interventions in works of Kuznetsov et al. (2011) and Stager (2013).

6.1.2 *Person-centered and Context-centered Constraints*

Based on our experiences, constraints can also be classified into two other categories – person-centered and context-centered constraints for making.

Person-centered constraints stem primarily from person-specific attributes and limits the person from taking part in making-centered activities. For example, in this dissertation, emotional or behavioral constraints for making can be considered primarily a person-centered constraint. Although specific issues such as lack of interest in technology-based activities, or low self-esteem can be a result of problems in the environment, such constraints are identifiable when observing individual people.

Context-centered constraints stem primarily from the environment in which the maker is present. For example, material and educational culture constraints stem primarily from broader economic or social factors.

The two categories are obviously interrelated – difficulties faced by a person can be a result of problems in their environment and vice versa (e.g., socially constructed gender differences). However, from a methodology standpoint, this rough two-level categorization can help researchers. Depending on the category of constraint, researchers can choose to spend time either focusing on observing people or in understanding more about a context. This in turn, could help researchers focus on generating human-centered (Cooley, 2000) or context-centered (Chen and Atwood, 2007) implications for technology design. For example, lessons learned from our study at the Kar School, such as difficulties of engaging with a school, and role of researcher are more context-centered than human-centered. The same pattern can be observed in the study by Sipitakiat et al. (2004), which suggested context-centered implications for technology such as use locally available materials, and locally manufacture tools. In contrast, our Maple study resulted in more human-centered lessons learned such as: types of student-centered tasks, possible entry points for students, and personal relevance for students.

6.1.3 *The Paradox of Constraints*

Lastly, we suggest that there is a paradox of constraints for making: constraints introduce tension to the creative process of making, which can inhibit creativity, but sometimes they also help provoke creative solutions. Three examples from our research demonstrate this.

In our study at the Kar School, during the workshop, one PC stopped working. We could not find an immediate or easy replacement within the workshop period, and therefore, one student group (G4) was forced to discard their project idea. In another instance, one student group (G2) was forced to reconsider their project idea because they did not have access to a soldering iron. In contrast, during the school science fair project, we saw that one student group (G1) creatively addressed lack of material resources by using other available materials (e.g., students used metal wire in place of a resistor).

In the Maple study, during Phase 1, starter kit activities, most students struggled with building projects using the LilyPad and Arduino. In Phase 1 of the study, only 2 of 8 students completed building projects. In contrast, during the open-ended projects, many (7 of 8) of the same students built 13 projects over three days using the Arduino. While student disliked the Arduino during Phase 1, students found working with the Arduino during Phase 2 creative.

In our study of the Polymorphic Cube, virtual properties of AR components restrict what makers can fully build and test. However, despite the limitations of AR components, participants' reaction showed that makers could use AR-mediated prototyping approach creatively for implementation tinkering, testing project ideas, and for making with others.

The identification of this pattern shows that the constraints, specifically in this dissertation, are not *all* disabling or enabling. Based on these instances, we think that the goal for researchers is to provide people with enough access to material resources, new tools, and varied opportunities that can serve as a starting point to be creative within constraints. For example, this could include providing different types of making-centered activities, or providing tools such as PMC that help makers continue to explore as much as possible despite a lack of electronics. Researchers have supported this view in creativity (Csikszentmihalyi, 1996; Joyce, 2009) and design (Gross, 1985). Csikszentmihalyi (1996) argues that while resources are crucial for creativity to develop, the solution to encourage creativity is not to provide excess resources. Instead, we should make material and intellectual resources widely available to all and know that certain amount of hardship might have a positive effect on creating.

6.2 CONSIDERATIONS FOR DESIGNING TECHNOLOGY

In this section, we present five considerations for designing future tools for makers. To generate implications for design we draw from our fieldwork data and design practice (Sas et al., 2014). Our list of considerations for design represents a starting point for thinking about how technology can be designed for makers within constraints, and is not meant to be an exhaustive list of all possible implications for design.

From previous literature, we know the following: (1) to address prohibitive cost concerns designers should focus on building low cost electronics, and support local manufacturing of physical computing kits (Sipitakiat et al., 2004). (2) To address restricted availability of materials, designers should focus on allowing the use of found and scrap materials (e.g., CD-ROM drive tray, optic sensor in a broken mouse, radio dial) for building circuits (Sipitakiat et al., 2004). (3) To address diversity of participation in programming activities, designers should focus on allowing learners to create many different types of personally meaningful projects, as well as make it easy for people to personalize their projects (Resnick et al., 2009). (4) At a methodology level, to encourage failure-positive mindset, researchers should verbally acknowledge that we learn from failed projects, and focus on iterative design process (Ryoo et al., 2015). We contribute to this existing body of knowledge by suggesting five additional considerations for designing tools for makers within constraints.

6.2.1 *ID1: Support Tinkering by Including Multiple Computing Platforms*

Tinkering, an experimental and iterative style of engagement is important to making-centered activities (Resnick and Rosenbaum, 2013). To tinker, makers need access to materials for making. However, in resource-constrained contexts makers have restrictive or no access to computational materials such as electronics and PCs. For example, from post-study interviews at the Kar School we learned that the school principal had securely locked away the electronics to avoid damage and distraction during examinations. Moreover, when resources (e.g., PCs, constructionist toolkits) are physically present, impoverished schools may not have the necessary IT support or the budget to repair or replace broken resources. For example, during day two of our workshop at the Kar School, one PC stopped working, and the school did not have IT support to repair the PC. As a result, one student group was forced to stop working on their project and had to join other student groups. The problem of material constraints also exists in less resource-constrained contexts, where makers may not have immediate access to resources. For example, as observed in a our study of Polymorphic Cubes, 11 of 12 makers had previously faced situations when they had to wait for electronic components to become available.

As an alternative to discarding project ideas and waiting for materials to become available, we propose that designers should focus on allowing makers to tinker as much as possible using other computing platforms such as phone, tablets, and wearables.

Polymorphic Cube (PMC) showed that makers can continue building physical projects using stand-in AR components created using paper-based QR codes and smartphones. In addition, previous research – such as TouchDevelop (Tillmann et al., 2011) and Bean [1] – has shown that opening up the ecology of maker tools to include alternative computing platforms, such as mobile phones and tablets, can help with hardware programming. With the improved computing power in such devices, and the widespread use of devices such as mobile phones in developing countries (Kumar et al., 2010) we think expanding the ecology materials to include multiple computing platforms such as mobile phones, tablets, and wearables would be more accessible and reliable to use for physical making among a wider, global audience.

6.2.2 *ID2: Facilitate Local Social Experiences*

Sharing is an explicit ethos of the Maker Movement (Silver, 2009). Sharing ideas and information digitally gives makers an opportunity to express themselves and help others (Kuznetsov and Paulos, 2010). However, in resource-constrained contexts, digital

1 https://punchthrough.com/bean

sharing is not always possible. For example, makers at the Kar School did not have access to Internet for digital sharing.

In resource-constrained contexts, sharing also takes a physical form – makers have to share devices and components. Due to limited availability of resources, physical sharing is often a necessity. For example, at the Kar School, because we only had 6 Arduinos for 12 students, students had to work on a project in groups of two or three.

To extend the benefits of sharing to makers, and to facilitate sharing of devices in resource-constrained contexts, we propose that designers should focus on creating tools and techniques that enable local social experiences.

Local social experiences can benefit from technology. For example, one way to capture and share student projects is by creating social support structures such as a local database of student project documentation. Pairing such technologies with additional tools that help create more process-focused documentation – such as capturing images of the circuit, capturing videos of circuit building, annotating circuits and programs – may help create local databases that are equivalent in content to websites such as Instructables.

For physical device sharing, extending previous approaches to sharing computing resources to making could help. For example, similar to community-based tangible programming (Horn and Jacob, 2007; Lo and Lee, 2016; Suzuki and Kato, 1993), techniques should be researched that enable multiple makers to interact with and manipulate the same physical computing device for programming and circuit building tasks.

6.2.3 *ID3: Help Novice Learners Fearlessly Explore Material Behaviors*

Identifying and understanding the behavior and possible failure modes of the hardware components is integral to physical computing. For example, a novice learner may not know what to expect when a photocell is connected to the rest of a circuit simply by looking at it. By using a photocell, the learner can develop an understanding of how it reacts to different light levels, or possible failure modes. For makers in resource-constrained contexts (e.g., Kar School students), however, they may only have limited independent learning resources to help guide or inform that exploration. Additionally, the risk of breaking components while exploring material comes at a high monetary and psychological cost. For example, due to the unavailability of Internet and independent learning resources such as textbooks or videos, one student group (G3) in the Kar School study could not find information about how to connect a temperature sensor. Because of the lack of information, G3 connected the temperature sensor wrong, resulting in a damaged sensor. The failed trial and error exploration made G3 fearful of using another temperature sensor.

We suggest that tools for physical computing should help novice learners identify, gain an understanding of, and encourage fearless exploration of the material behaviour with minimal cost investment.

Technology can help fearless exploration. For example, Fearless cards, a set of basic computer literacy instructions, help underserved communities such as Hispanic day laborers overcome emotional barriers to learn computer and Internet use (Gomez et al., 2013). Additionally, simulation systems such as Circuits.IO (Circuits, 2017) that use virtual components could also help fearless exploration of material behaviors. Because the components are virtual, there is no risk of physically breaking the electronic components.

We suggest expanding this body of research to work within the traditional electronics ecosystem that uses breadboards, electronics, and a microcontroller for building interactive physical systems.

6.2.4 *ID4: Enable Creative Authorship*

Self-directed experimentation is necessary for making-centered activities. However, some traditional education cultures oppose the DIY approach to problem solving (Resnick and Rosenbaum, 2013). For example, at Kar School, students are traditionally trained to follow the teacher's instructions. During our study, we observed that G3 refused to experiment beyond the one-LED-blinking exercise; we did not provide any explicit instructions for how to continue exploring their circuits. In contrast, G1, by trial and error, connected multiple LEDs to their circuit. Moreover, when students found the necessary intellectual courage to experiment, we saw that students (e.g., G6) learned new things and enjoyed the process of discovering new possibilities for furthering their project ideas. This design consideration can also be useful for at-promise and similar youth groups who tend to dislike instruction following approaches to experimentation and prefer to have more control over the creative process and do not like to follow instructions.

We suggest that interaction designers should help makers gain creative authorship over the making process by transitioning from an instruction following approach to problem solving, to a DIY approach to problem solving.

Previous research has demonstrated examples – such as d.tools (Hartmann et al., 2006), Maker's Mark (Savage et al., 2015), and Pineal (Ledo et al., 2017) – which allow makers to author a specific process in making (e.g., authoring programming or enclosure fabrication). We encourage designers to expand this body of research to work with other aspects of making (e.g., authoring circuit building).

6.2.5 *ID5: Help Build Personally Relevant Tangible Experiences*

People learn best, and enjoy most, when working on personally meaningful projects (Resnick et al., 2009). Based on this view, diversity is an important design priority (Resnick et al., 2009).

At present, makers have access to several general-purpose constructionist toolkits (e.g., Arduino, Raspberry Pi, Phidgets). Using these kits, makers can build a variety of projects. However, general-purpose microcontrollers do not necessarily address diversity; the focus is still on foregrounding technical skills such as building and debugging circuits, and programming (Collective and Shaw, 2012). However, as observed from Maple study, not all makers are interested in learning electronics and becoming software developers. One participant explicitly mentioned that she would like to combine art with electronics. We suggest that designers should focus on developing building blocks that hide the technical details and instead represent more expressive mediums.

We suggest that designers should build new technologies that allow makers to express themselves by building personally relevant tangible experiences.

Previous research such as MaKey MaKey show how makers can build touch interfaces by connecting objects such as apples and bananas to the microcontroller using alligator clips (Collective and Shaw, 2012). The simplistic circuitry allows makers to focus on creating interesting touch interface-based projects using novel objects without worrying about details such as interpreting circuit diagrams, building and debugging circuits, and programming. We suggest that designers could extend such approaches to other application areas such as games, storytelling and visualizations to create personally meaningful tangible experiences.

6.3 Conclusion and Future Work

In this Chapter, we discussed two main themes of this dissertation – constraints and technologies for making. Related to constraints, we discussed three characteristics of constraints for making. Based on our exploration of making within constraints, we described five considerations for technology design that might help in the development of maker tools that are more broadly useful for diverse makers.

Our list of characteristics and implications for design are new and have little validation outside the background work presented in this dissertation. Future studies should continue to build on these characteristics and implications for design.

7

CONCLUSION AND FUTURE WORK

In Chapter 1 of this dissertation, we introduced the overarching goal of this research: **exploring *making within constraints*.** With this in mind, this dissertation had two subgoals:

- **Goal 1. Understand how people respond to making within material, cultural, and emotional or behavioral constraints.**
- **Goal 2. Investigate how technology can help making within constraints.**

In this conclusion chapter, we first revisit the research goals, then we revisit the research contributions, and then conclude with suggestions for future research.

7.1 REVISITING THESIS GOALS

In this section, we begin by reviewing the progress we have made towards the dissertation goals introduced in Chapter 1.

7.1.1 *Goal 1. Understand how people respond to making within material, cultural, and emotional or behavioral constraints.*

Our two studies discussed in Chapters 3 and 4 represent two instances of research that offer an in-depth discussion of how contextual constraints affect the Maker Movement from taking hold (Somanath et al., 2016, 2017). Much of the HCI literature, with the exception of a few that have examined this movement with a critical lens (e.g., Ames et al., 2014; Bean and Rosner, 2014), have celebrated the advent of the Maker Movement. Our studies highlighted that while some people respond positively to making despite constraints, many others find it difficult to continue to persevere with challenges that are fundamental to making. For example, an understanding of technical knowledge such as programming and electronics is important to physical computing. In current HCI studies of making-centered workshops the challenge of limited technical knowledge is often attributed to common problems faced by novice makers (e.g., Buechley et al., 2008). However, contextual problems such as limited prior hands on experiences, no access to independent learning resources such as Internet, and gaps in education go beyond problems faced by novices and create roadblocks to taking part in making-centered activities. In this dissertation, we make progress towards Goal 1 by identifying both challenges and strategies of makers for making within material, cultural, and emotional constraints. Going forward, we hope that our findings and lessons learned serve as pointers to future researchers and guide them develop resources (at both empirical and design-level) which can be made widely accessible for diverse makers.

7.1.2 *Goal 2. Investigate how technology can help making within constraints.*

In this dissertation, informed by our studies we make progress towards Goal 2 by suggesting a set of implications for technology design, by proposing a technology solution that can help makers continue to make despite materials constraints, and by demonstrating a working prototype system, Polymorphic Cube (PMC). In Chapter 5 we proposed a vision for *AR-mediated prototyping* – a way to help makers continue to build physical projects despite missing I/O components. Based on our vision, we designed and implemented a technology probe, *Polymorphic Cube (PMC)*. This work demonstrated that technology can help makers continue to build as much as possible and explore ideas when they do not have immediate or easy access to materials. This exploration serves as an inspirational example for other researchers interested in proposing tools for creating physical projects when makers do not have the required materials for making.

7.2 REVISITING THESIS CONTRIBUTIONS

In Chapter 1, we outlined the contributions of our work on *making within constraints*. In this section, we revisit those contributions. We make six contributions to the research into *making within constraints*:

1. **We contribute findings from a study that examines making within material and educational culture constraints.**

   In Chapter 3, we discussed a workshop-based study conducted at an impoverished high-school in India. The goal of the study was to understand how students within material and educational culture constraints react to DIY making-centered activities. From this study, we learned about both challenges and the strategies of makers for taking part in making-centered activities.

2. **We contribute findings from a study that examines making within emotional or behavioral constraints.**

   In Chapter 4, we discussed a two-phase study conducted to explore ways to engage at-promise youth in DIY making-centered activities. Overall, we learned that makers within emotional or behavioral constraints like to have control over the creative process of making, and that open-ended activities can help facilitate such control.

3. **Informed by our studies, we contribute a set of implications for research.**

   In Chapters 3 and 4, we discussed a set of lessons learned that can inform future researchers interested in conducting making-centered workshops within material, educational culture, and emotional or behavioral constraints.

4. **We propose a vision for designing Augmented Reality (AR)-mediated prototyping tools for making within material constraints.**

   In Chapter 5, we discussed our vision for designing AR-mediated prototyping tools that can allow makers to continue to build physical projects despite material constraints. AR-mediated prototyping tools allow makers to blend virtual and real-world prototyping materials and build, interact with, and program unified physical projects. In our vision, we discussed four aspects for design consideration including physical and virtual form, circuitry and programming, physical interactions, and social interactions. We also suggested a set of possible tasks for such tools.

5. **We contribute the design, implementation, and evaluation of a technology probe, Polymorphic Cube (PMC), based on our vision of AR-mediated prototyping.**

   In Chapter 5, we described our implementation and evaluation of Polymorphic Cube (PMC) based on our vision for AR-mediated prototyping tools. PMC allows makers to continue building physical circuits despite missing electronic components. Our evaluation of PMC showed that it was helpful not only to address lack of electronic components, but is also potentially useful for exploring and testing project ideas, implementation tinkering, and making with others.

6. **Informed by both our empirical and design explorations, we contribute a set of characteristics for constraints and implications for technology design.**

   In Chapter 6, we introduced and discussed three characteristics for constraints for making. In addition, we suggested five implications for designing future tools for diverse makers.

7.3 FUTURE WORK

We previously discussed the immediate future work specific to each of the concepts presented in Chapters 3- 6 (see Sections 3.8, 4.7, 5.6, and 6.3). In this section, we discuss general directions for three categories of future work: empirical-level, design-level, and theoretical-level.

7.3.1 *Empirical-Level Future Work*

Two broad avenues for future studies include:

- To fully validate the usability of maker tools such as PMC, it will be necessary to conduct in-the-wild studies in schools, libraries, or makerspaces with specific end-user groups. Such studies can help identify the discrepancy between pure research thinking and practical needs (e.g., Buechley and Hill, 2010). However, we posit that designers have to build high-fidelity systems and address certain challenges that are prevalent in certain contexts (e.g., setup the necessary infrastructure, convince teachers to incorporate such tools in curriculum) before conducting such in-the-wild evaluations.

- Second, it would be interesting to conduct a study that helps develop and validate a standard coding scheme (Goodwin, 1994). Some examples of categories in such a coding scheme could include: maker demographics (e.g., children, teenagers, adult, older adults), type of constraint (e.g., material, culture, emotional, behavioral), effect of constraint on maker or design process (e.g., lack of motivation, tendency to give-up, scarce material availability), hardware tools (e.g., Arduino, Makey-Makey, LilyPad), software tools (e.g., Scratch, Ardublocks, Arduino IDE), goal of study (e.g., learn about challenges and strategies of makers faced with resource limitations, teach technical skills, measure technology literacy) and lessons learned. A standard coding scheme could help introduce a structure to the exploration of *making within constraints* and could help researchers compare and contrast results of studies about maker practices.

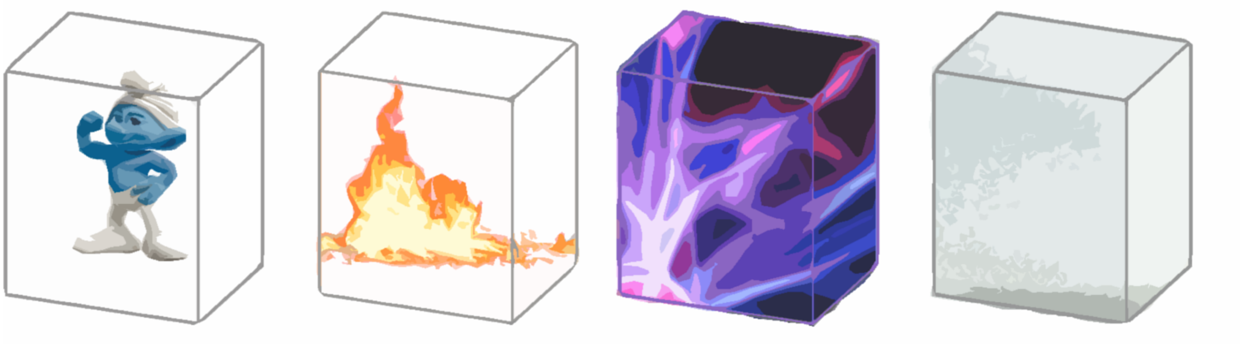


Figure 49: A sketch of character, fire, light, and fog magic cubes.

7.3.2 *Design-Level Future Work*

In this dissertation, we proposed and designed a tool for addressing material constraints. In the future, there are other possible paths to explore for developing tools that address other types of constraints. In this section, we describe an idea for a possible future maker tool for addressing emotional or behavioral constraints: Magic Cubes.

The goal of Magic Cubes is to help makers within emotional or behavioral constraints to express themselves using computational materials. Literature has highlighted that the use of expressive art mediums such as paint, clay, music, and poetry can help facilitate expression in traumatized children (Wikström, 2005) and can help them deal with crises and trauma (Coholic et al., 2012). Creative edutainment systems, such as storytelling systems, have been found to motivate socio-cultural awareness among children and youth (e.g., Zin and Nasir, 2007). Research has also shown that artistic expressions can help adolescents to shape and build identities. For example, Fisher (2004) found that anime characters, a Japanese animation art, helps adolescents to build positive identities similar to their favourite characters. Based on this, we propose an idea for building a set of expressive building blocks, Magic Cubes, for creating physical interactive systems.

Traditionally, the building blocks for creating physical computing projects using constructionist toolkits are electronic components (e.g., servo, slider, LED, speaker). In addition to using electronics, what if makers could build physical interactive systems using a set of alternative controllable elements such as text, 3D models of cities and characters, and natural elements (e.g., fire, light, and water)? We envision Magic Cubes (Figure 49), as a set of expressive building blocks for creating physical interactive systems. Magic Cubes encapsulate expressive art materials and so-called magical objects (Thompson, 1977) inside a physical block and "hide" the electronic components (Figure 49). Makers can use Magic Cube-like tools to build artifacts (e.g., interactive storytelling installation, tangible game), as a means of self-expression.

To build a physical artifact, we envision makers could attach different types of cubes together, similar to LEGO blocks. In addition, we envision that makers can control and interact with the Magic Cubes using traditional electronics and programming. For example, a fire cube can be an analog component, whose animated states can be controlled via a programmed slider component. Interactions such as attaching cubes, shaking cubes, and manipulating cubes can alter how a system responds. For example, attaching a water cube to a fire cube can extinguish the fire cube.

Keeping in mind the target audience for this tool (at-promise makers), in the future, we suggest implementing Magic Cubes as physical tokens. We envision that the physicality of Magic Cubes will lower the threshold for interaction (Ishii and Ullmer, 1997; Zuckerman et al., 2005; Ishii, 2008), specifically for younger at-promise children. Moreover, Constructionism (Papert and Harel, 1991) proposes that use of tangible objects helps create a more shareable experience. Shared experiences can be useful for improving interpersonal skills of at-promise makers. In the short term, Magic Cubes can be implemented using a variety of technologies such as Augmented Reality (e.g., Google Tango), Virtual Reality (e.g., Oculus Rift), or Hologram technologies (e.g., Microsoft HoloLens).

7.3.3 *Theoretical-Level Future Work*

In the long term, it can be interesting to develop a framework for *making within constraints*. We envision that such a framework will help identify a more exhaustive list of constraints and provide directions for how new technologies for diverse makers can be built. Similar to framework for TUIs (Ullmer and Ishii, 2000), a framework for maker tools can establish a design space by identifying: types of constraints (e.g., material resources, culture, emotional or behavioral) functions of systems in each category (e.g., support design iteration, facilitate circuit building, create enclosures), and the application domains (e.g., physical user interfaces, e-textile, fabrication, education, programming systems). We posit that more prototypes need to be built first to develop such a framework.

7.4 CLOSING REMARKS

With the emergence of the Maker Movement and its promised benefits for people (e.g., independence, creativity, and agency), researchers and interaction designers should think about how diverse groups of people can get involved in making-centered activities. This dissertation, contributes to exploring *making within constraints* via a set of lessons learned from observing maker practices within material, education culture, and emotional constraints, and demonstrates a tool that can address making with material constraints. As discussed in our future works, there are several possibilities for taking this work further. We hope the work presented in this dissertation will inspire researchers and interaction designers in future endeavors of understanding making within constraints, and developing tools that eventually help resolve the different types of constraints that inhibit the Maker Movement from taking hold.

A

ADDITIONAL MATERIALS FOR KAR SCHOOL STUDY

A.1 QUESTIONNAIRES

For additional details about the procedure used in the Maple study, we include the pre-study questionnaire and post-study semi-structured interview questions below.

A.1.1 *Pre-Study Questionnaire*

1. Name
2. Age
3. Gender
4. Grade
5. Father's occupation
6. Mother's occupation
7. Sibling occupation

8. From how long have you been using a computer?
9. What do you use the computer for?
10. Do you own a computer at home?
11. Do you have access to a mobile phone at home?
12. Do you use use the mobile phone? If yes, what do you use the mobile phone for?
13. Have you done any computer programming before? If yes, which language do you use?
14. Have you learnt about electrical circuits in school?
15. Have you heard about arduino's?

A.1.2 *Semi-Structured Interview Questions*

1. Do you feel you learned something from this workshop? What?
2. Do you think participating in this workshop helped you? How?
3. Do you feel like you have some understanding of electrical circuits?
4. What was most difficult in the process of building projects?
5. How many found programming understandable? Difficult? Easy?
6. How many found circuitry understandable? Difficult? Easy?
7. Do you think you see yourselves using the Arduino past this workshop timeline? How would you use it?

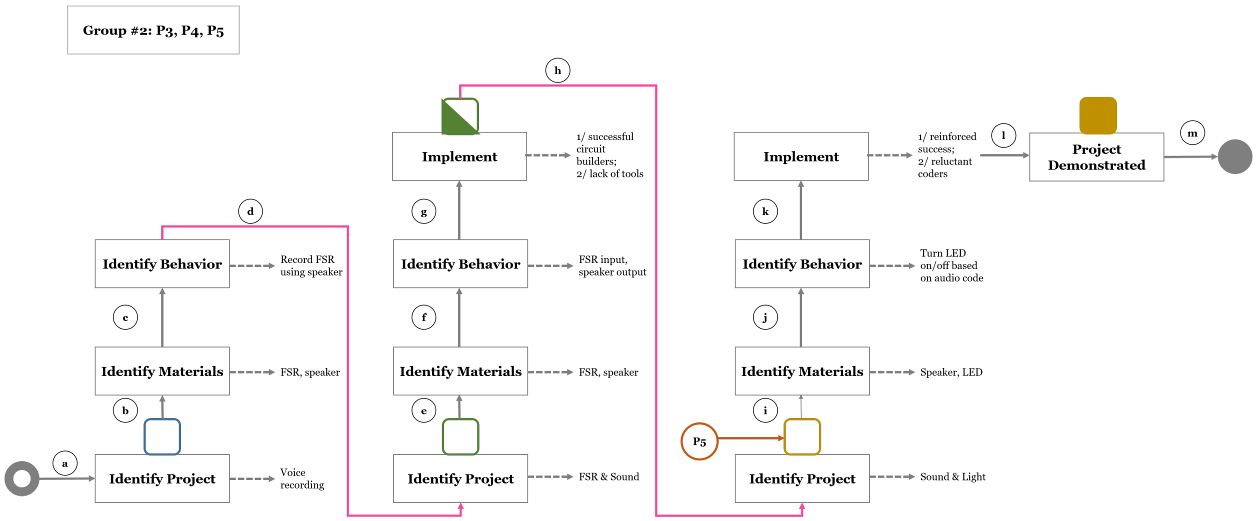


Figure 50: Workflow diagram of Group 2.

8. Did you enjoy the workshop? Did you have fun?

9. Do you have any suggestions for how we can improve the workshop in the future?

A.2 WORKFLOW DIAGRAMS

We traced each student group's workshop journey from project identification to project demonstration as workflow diagrams. Figures 50, 51, 52, 53, and 54 represent workflow diagrams for Groups 2-6. Workflow diagram for Group 1 was discussed in Chapter 3. Details of data analysis methodology was also discussed in Chapter 3.

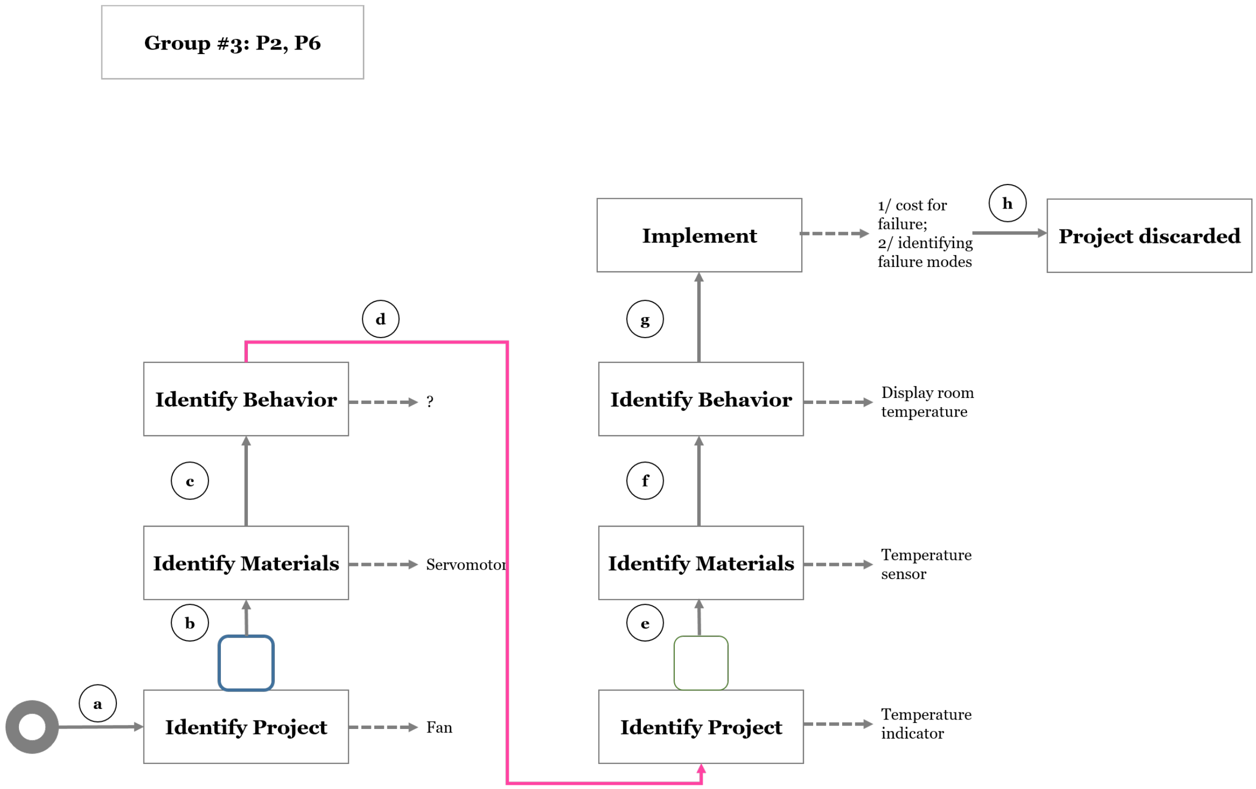


Figure 51: Workflow diagram of Group 3.

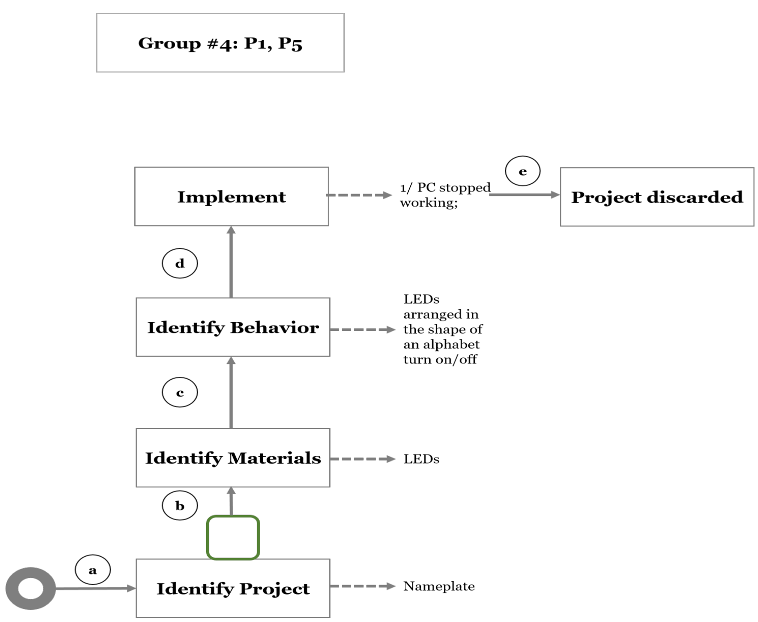


Figure 52: Workflow diagram of Group 4.

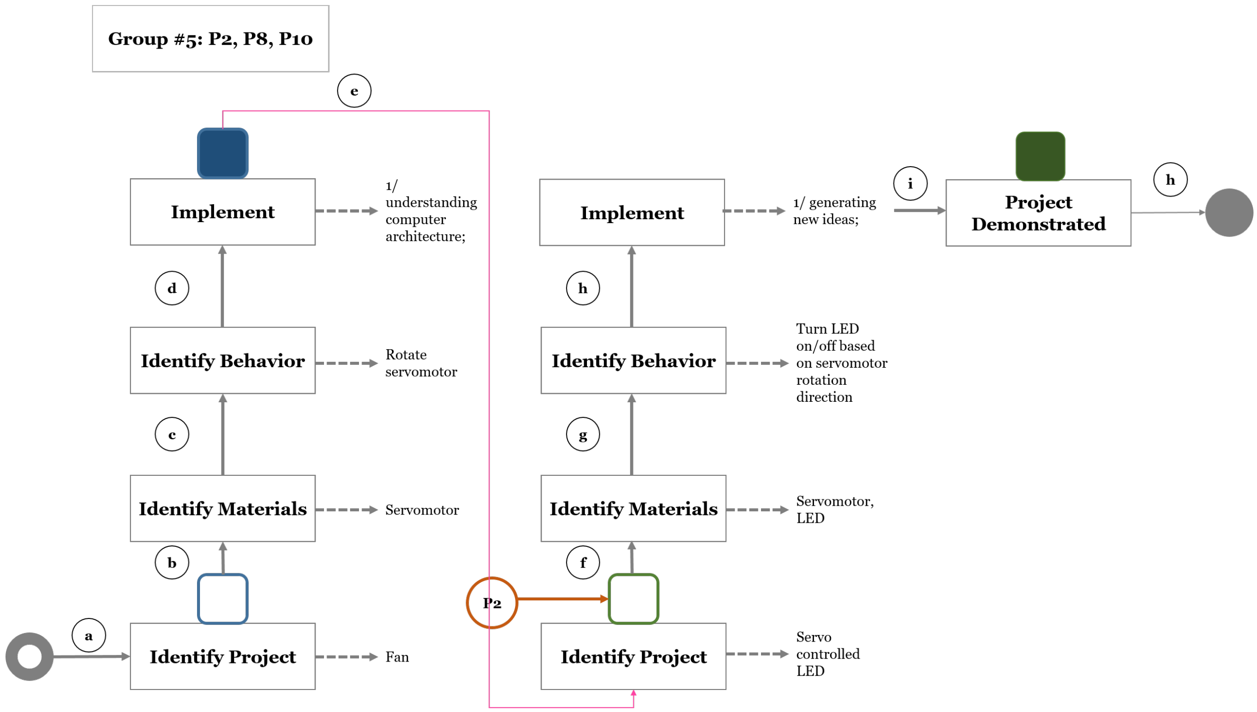


Figure 53: Workflow diagram of Group 5.

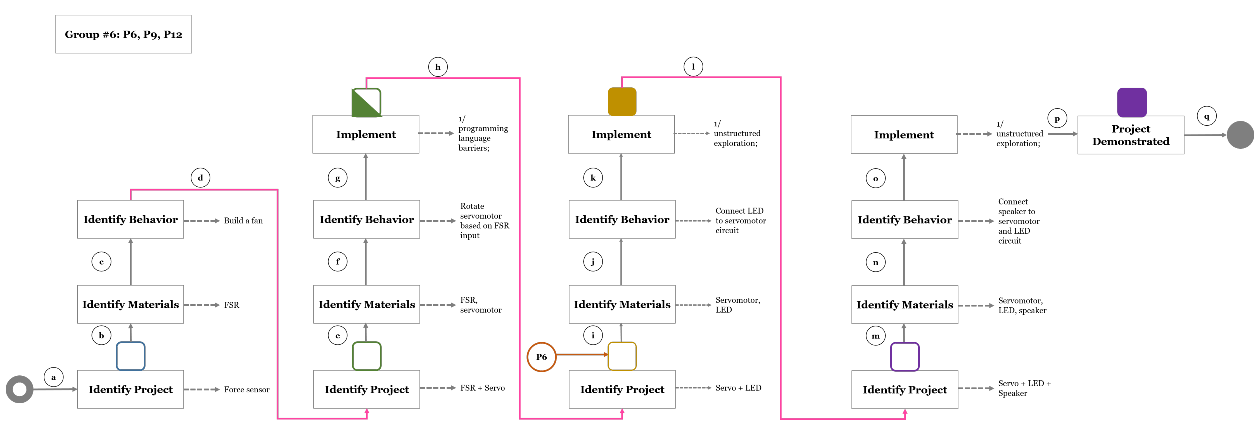


Figure 54: Workflow diagram of Group 6.

B

ADDITIONAL MATERIALS FOR MAPLE STUDY

B.1 QUESTIONNAIRES

For additional details about the procedure used in the Maple study, we include the pre- and post-study questionnaires, and semi-structured interview questions below.

Pre-Study Questionnaire

Participant number:

1. Name:
2. Age:
3. Gender:
4. Grade:
5. List the electronics (Arduino's, Makey-Makey etc.) that you have explored previously:
6. For how long have you been exploring Arduino:
7. List the programming languages and/or programming environments you are familiar with:
8. For how long have you been programming:
9. Do you own a personal computer?
10. What do you commonly use the computer for?
11. Do you own a mobile phone?
12. What do you commonly use the mobile phone for?
13. Statement responses:

Statement	**Strongly agree**	**Agree**	**Neutral**	**disagree**	**Strongly disagree**
I feel comfortable programming computers on my own.					
I feel comfortable building electronics on my own.					
I enjoy programming computers.					
I enjoy building electronics.					
I think programming will be a useful skill to learn for my future.					
I think learning to build using electronics will be a useful skill for my future.					

14. Complete the below responses:

    a. I would enjoy programming more if:
    b. I would enjoy building electronics more if:
    c. I enjoy the following activities at school:
    d. An electrical circuit is:
    e. A software program is:

Post-Study Questionnaire

Participant number:

1. Name:
2. What project(s) did you work on in the workshop?
3. Statement responses:

Statement	**Strongly agree**	**Agree**	**Neutral**	**disagree**	**Strongly disagree**
I feel comfortable programming computers on my own.					
I feel comfortable building electronics on my own.					
I enjoy programming computers.					
I enjoy building electronics.					
I think programming will be a useful skill to learn for my future.					
I think learning to build using electronics will be a useful skill for my future.					
I liked the project(s) I worked on. Project 1: Project 2:					
I enjoyed the workshop					

4. Complete the below responses:

   a. I would enjoy the workshop more if:
   b. I would like my project(s) more if:
   c. After the workshop I feel I learnt:

Semi-Structured Interview Questions

1. Do you feel like you learned something from this workshop? What did you learn?
2. Do you feel like you have a better understanding of circuits? Can you describe what a circuit is?
3. Do you feel like you have a better understanding of coding? Can you describe it?
4. How did you feel about working with Arduinos this time around?
5. What was different this time?
6. Did it work better this time?
7. What was your favorite part over these 3 days?
8. Was there anything boring or frustrating?
9. How much did you reply on peers for help and how much did you help others?
10. How did asking for help make you feel?
11. What did you do to start planning your projects?
12. What did you do when you were stuck?
13. Would you want to continue with circuits and programming in school or at home?
14. Can you think of other times you might use programming or circuits in the future?
15. Do you see this linking into your future career plans?
16. Any additional questions or comments for us?

SUSHI TABLE Build a rotational sushi table.	**ELEVATOR** Build an elevator for Tiny Lego people.	**ANGULAR SPEED** Build a controllable rotational platform or disc to demonstrate angular speed.	**BOILING POINT** Build a system that demonstrates boiling point.
BED LIGHT Build a bed light for tiny Lego People.	**THERMOSTAT** Build a simple thermostat for water.	**DIRECTION CONTROL** Build a simple system that can arrange objects as directed by you.	**SAFETY** Build a pulley system that tests safety control – that is, the door of the carrier must be kept close as long as the pulley is moving.
SUNBLIND Build a controllable sunblind system.	**WIPER** Build a controllable windshield wiper for toy cars.	**BRIGHTNESS CONTROLLER** Build a light source whose brightness can be controlled by you.	**PENDULUM** Build a controllable pendulum to demonstrate mass and length.
ROBOT Build a simple friendly crane robot that can move small building blocks.	**Swing** Build a controllable swing for tiny Lego people.	**MECHANICS** Build a controllable system that demonstrates how uniform surfaces can be cleaned.	**NATURAL LIGHT REGULATOR** Build a controllable system that regulates the amount of natural light for a room.

Figure 55: Real-world (columns 1-2) and Abstract (columns 3-4) project cards.

B.2 PROJECT CARDS

For additional details about the project cards used during the study, we include the sixteen project cards for the Maple study (see Figure 55).

C

ADDITIONAL MATERIALS FOR AR-MEDIATED PROTOTYPING AND POLYMORPHIC CUBE

C.1 QUESTIONNAIRES

For additional details about the procedure used in the Polymorphic Cube studies, we include the pre- and post-study questionnaires, code samples, the online questionnaire.

Polymorphic Cubes: Pre Questionnaire

1. **Participant number**

2. **Name**

3. **Age**

4. **Profession (e.g. student, designer, artist)**

5. **Discipline**

6. **Experience with physical computing - building interactive systems using programmable electronics**
   Mark only one oval.
   - Expert
   - Competent
   - Beginner
   - Novice

7. **Involved in physical computing activities**
   Mark only one oval.
   - Frequently
   - Occasionally
   - Rarely
   - Never

8. **What kind of things do you build using Ardunio or other physical computing tools?**

9. **Have you experienced a situation when you designed/ planned a system you wanted to build/prototype but later found that you were missing one or more electronic components that you needed?**

Mark only one oval.

- Yes
- No

10. **If you answered yes to the above question, please explain what you did to overcome the lack (missing component situation)**

Post Questionnaire

1. **How difficult was it to understand the concept of polymorphic cube?**
Mark only one oval.

- Very difficult
- Difficult
- Neutral
- Easy
- Very easy

2. **Overall how usable was the polymorphic cube?**
Mark only one oval.

- Never
- Almost never
- Occasionally/ Sometimes
- Almost every time
- Frequently

3. **How difficult was it to program the polymorphic cube?**
Mark only one oval.

- Very difficult
- Difficult
- Neutral
- Easy
- Very Easy

4. **How difficult was it to build circuits using the polymorphic cube?**
Mark only one oval.

- Very difficult
- Difficult
- Neutral
- Easy
- Very easy

5. **How different was your experience working with a virtual actuator (i.e. polymorphic cube servo) in comparison to a physical actuator (i.e. real servo)?**
Mark only one oval.

- Much worse
- Somewhat worse
- About the same
- Somewhat better
- Much better

6. **How different was your experience working with a virtual component (i.e. polymorphic cube pushbutton) in comparison to a physical component (i.e. real pushbutton)?**
Mark only one oval.

- Much worse
- Somewhat worse
- About the same
- Somewhat better
- Much better

7. **How different was your experience working with a virtual sensor (i.e. polymorphic cube photocell) in comparison to a physical component (i.e. real physical component)?**
Mark only one oval.

- Much Worse
- Somewhat worse
- About the same
- Somewhat better
- Much better

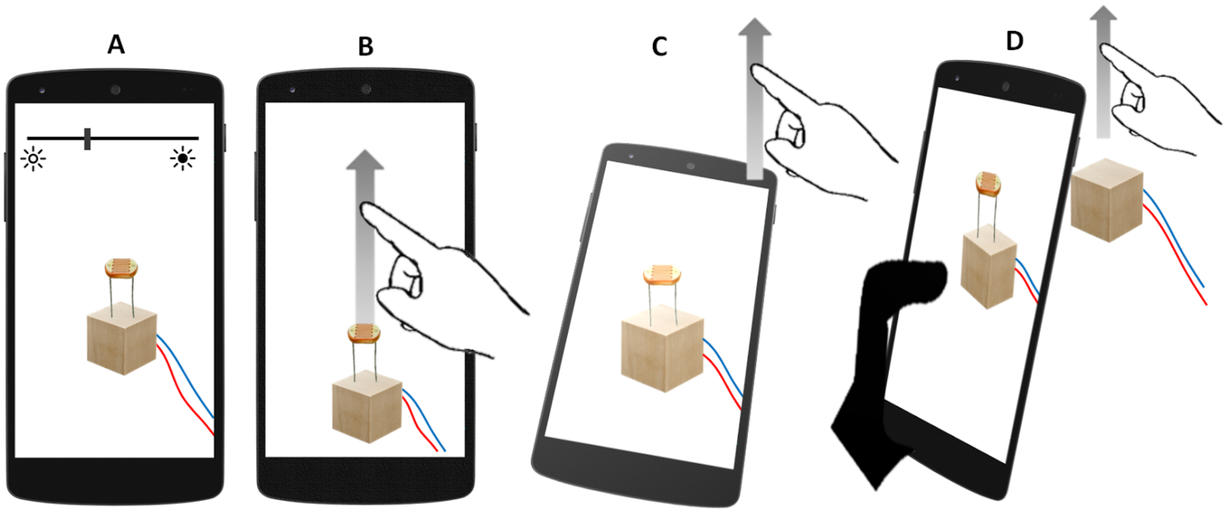
Polymorphic cube - Interaction Styles

* Required

1. **Name** *

Polymorphic cube - Interaction Styles

Interaction Styles for Polymorphic Cube



The above figure illustrates four ways to interact with an analog (continuous value) polymorphic cube electronic component:

(A) : Interaction using a slider widget on the phone screen.

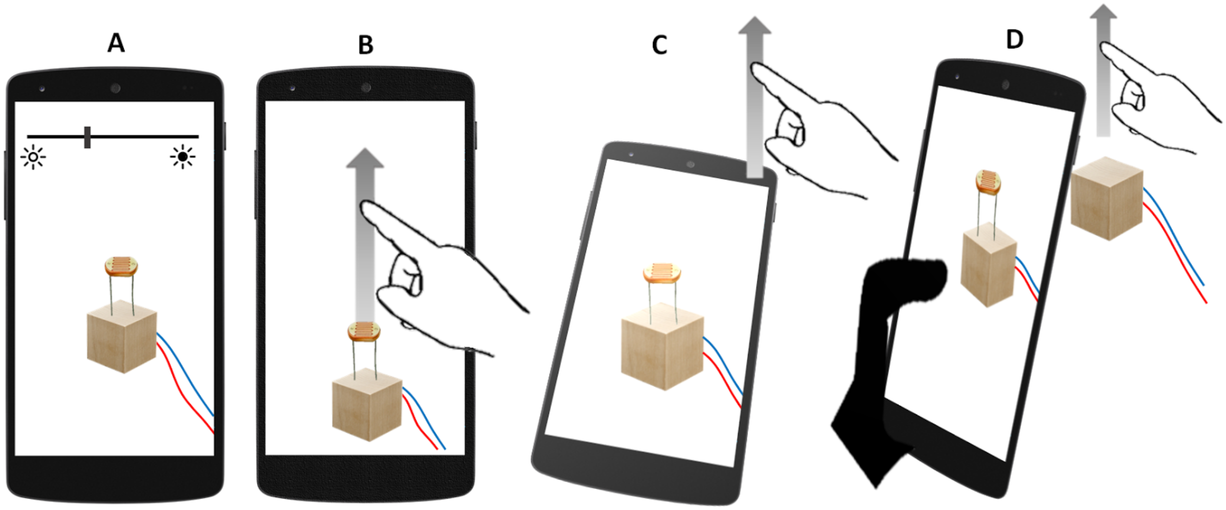
(B) : Touch based interaction with the virtual electronic displayed on the phone screen.

(C) : Interaction facilitated via inbuilt phone sensors. Typically, the following sensors are present in recent smartphones:
1. Accelerometer
2. Gyroscope
3. Ambient light sensor
4. Temperature and humidity sensor
5. Proximity sensor
6. Magnetometer sensor
7. Microphone
8. Speaker
9. Camera

(D) : Mid-air gesture interaction.

Example

Interaction Styles for Polymorphic Cube



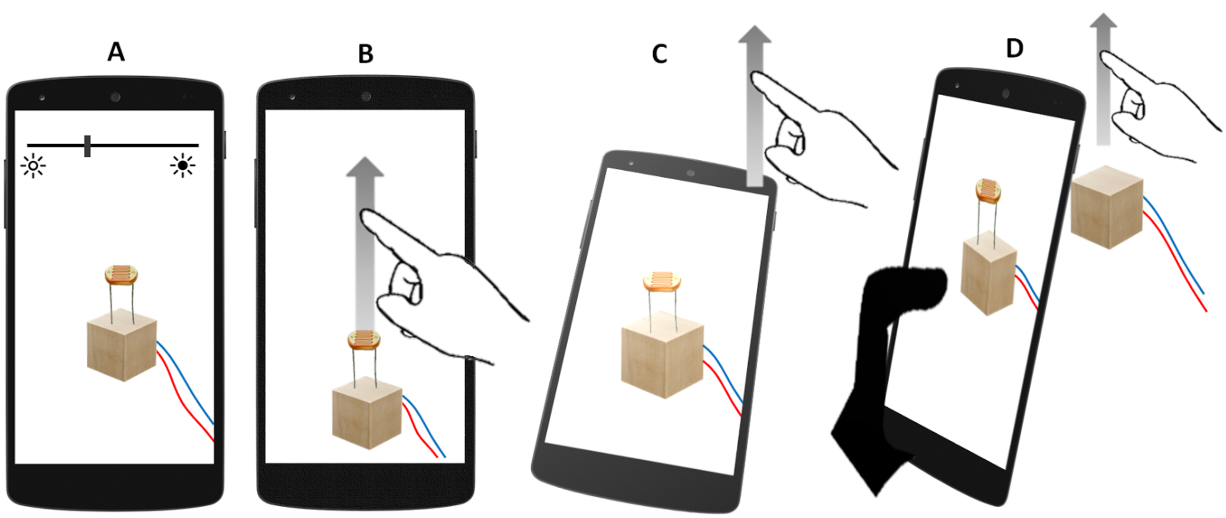
Interacting with a photocell

The above figure illustrates the case of a polymorphic cube photocell.
• (A) : The amount of light received by the photocell is controlled using a slider widget on the phone screen.
• (B) : The amount of light received by the photocell is controlled by covering/ uncovering the photocell (as done during the study).
• (C) : The amount of light received by the photocell is controlled by interacting with the inbuilt ambient light sensor of the phone.
• (D) : The amount of light received by the photocell is controlled via mid-air interaction.

Question 1 - Light sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



2. **Please rank the following interaction styles in order of preference for light sensors (e.g. photocell).** *
Mark only one oval per row.

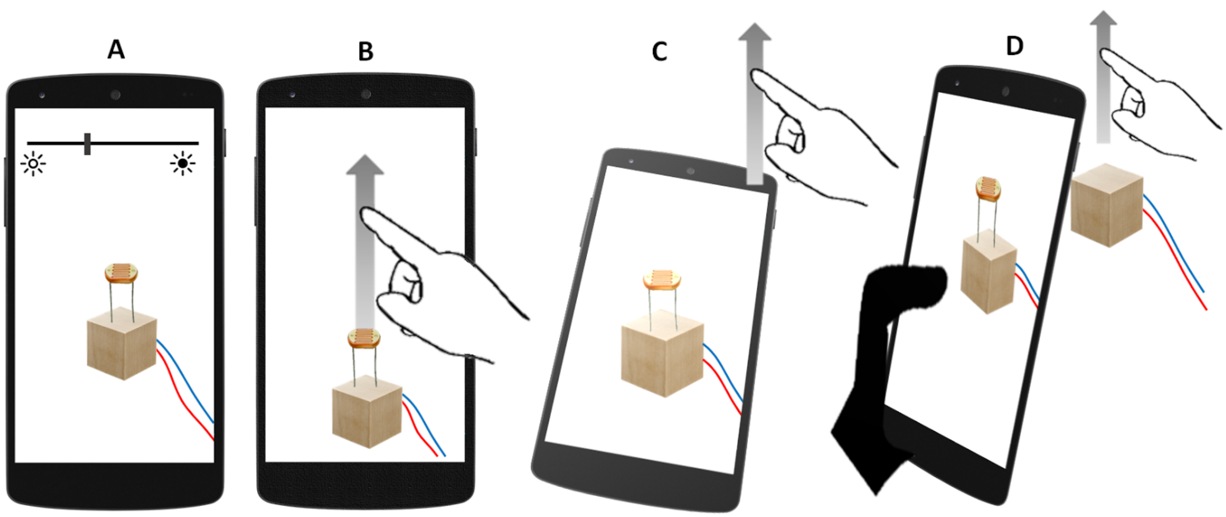
	1 (Most Preferred)	2	3	4 (Least Preferred)
A	◯	◯	◯	◯
B	◯	◯	◯	◯
C	◯	◯	◯	◯
D	◯	◯	◯	◯

3. **Describe the rationale behind your ranking:** *

Question 2 - Weather sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



4. **Please rank the following interaction styles in order of preference for weather sensors (e.g. temperature, humidity, oxygen, carbon monoxide, dust etc.).** *
Mark only one oval per row.

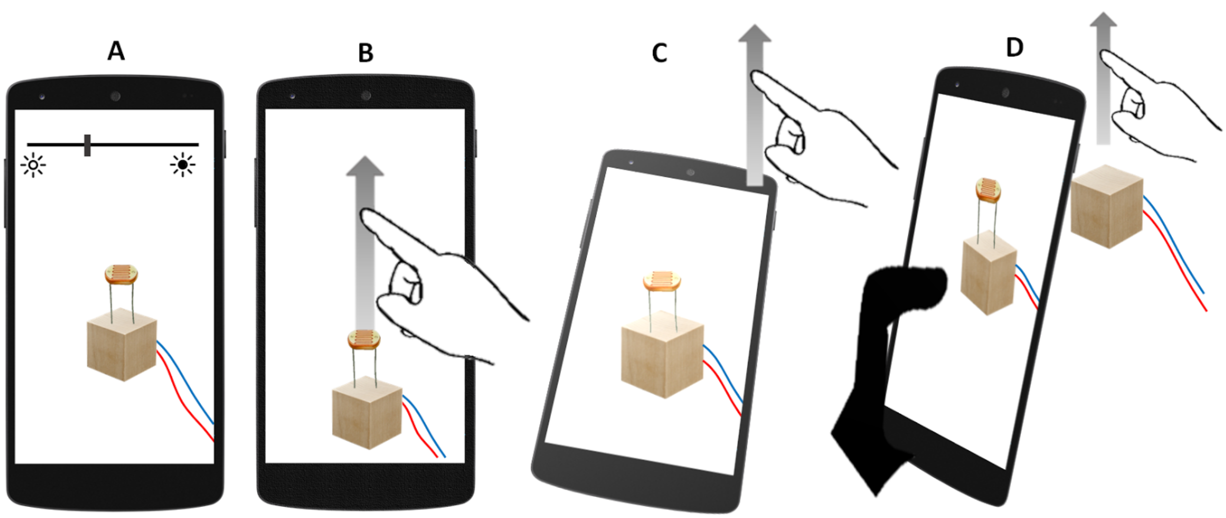
	1 (Most Preferred)	2	3	4 (Least Preferred)
A	◯	◯	◯	◯
B	◯	◯	◯	◯
C	◯	◯	◯	◯
D	◯	◯	◯	◯

5. **Describe the rationale behind your ranking:** *

Question 3 - Flex, Force & Vibration sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



6. **Please rank the following interaction styles in order of preference for flex, force and vibration sensors.** *

Mark only one oval per row.

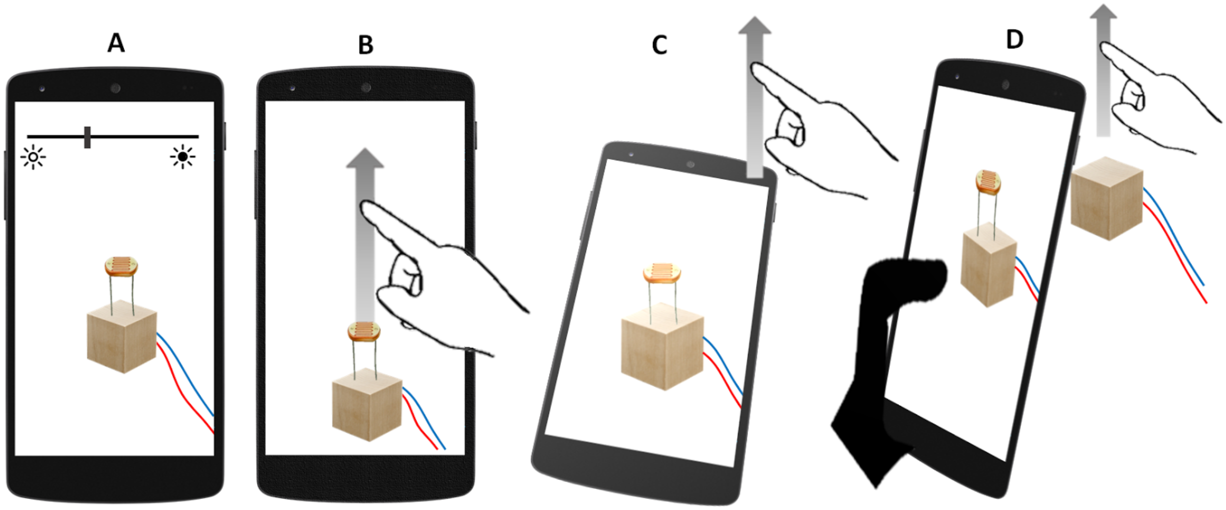
	1 (Most Preferred)	2	3	4 (Least Preferred)
A				
B				
C				
D				

7. **Describe the rationale behind your ranking:** *

Question 4 - Direction sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



8. **Please rank the following interaction styles in order of preference for direction sensors (e.g. accelerometers, gyroscope).** *
Mark only one oval per row.

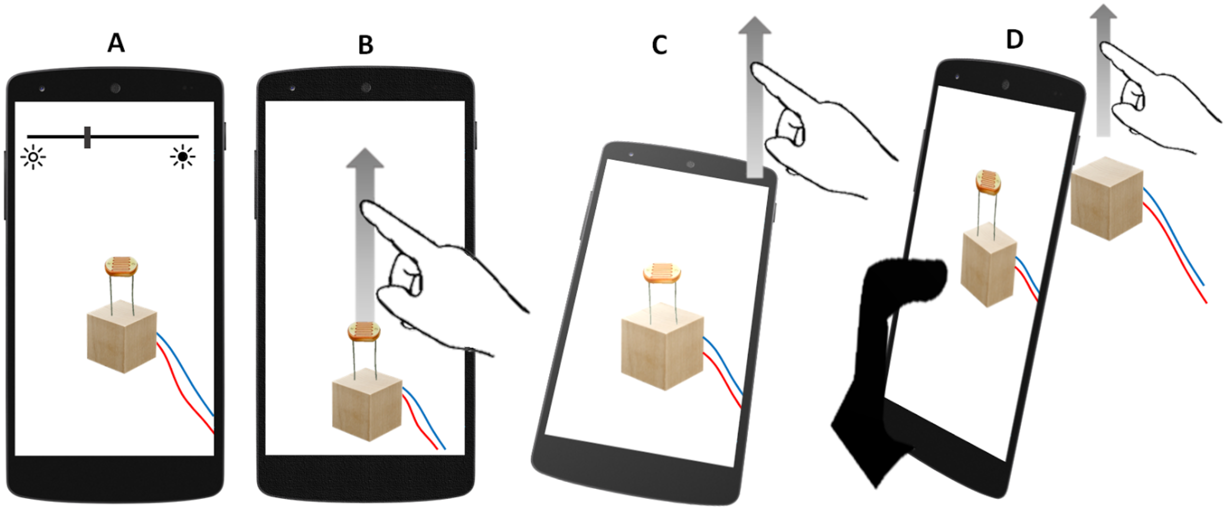
	1 (Most Preferred)	2	3	4 (Least Preferred)
A	◯	◯	◯	◯
B	◯	◯	◯	◯
C	◯	◯	◯	◯
D	◯	◯	◯	◯

9. **Describe the rationale behind your ranking:** *

Question 5 - Distance sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



10. **Please rank the following interaction styles in order of preference for distance sensors (e.g. proximity, magnetic, sonar).** *
Mark only one oval per row.

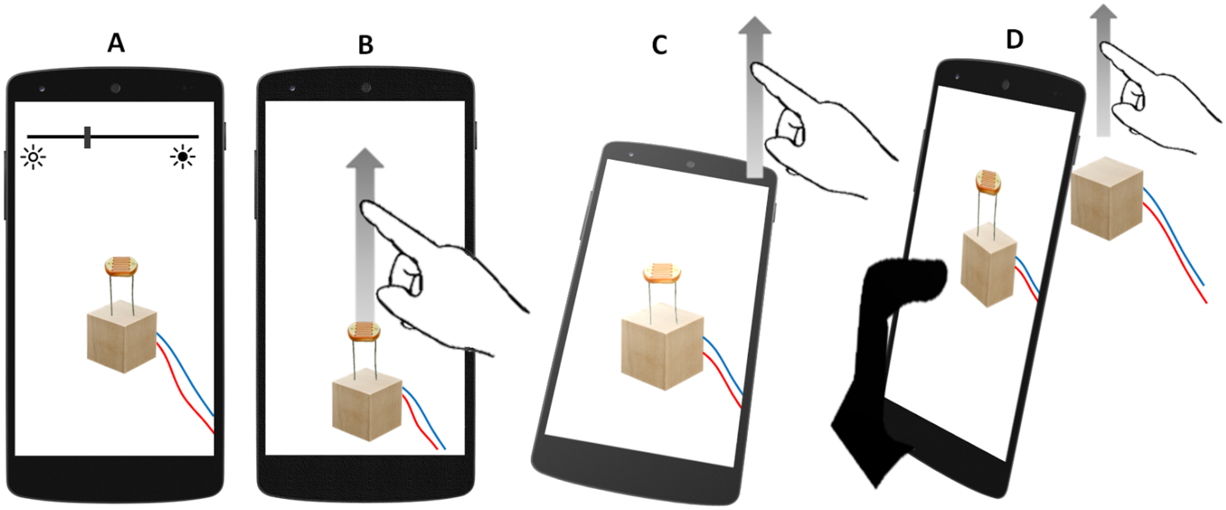
	1 (Most Preferred)	2	3	4 (Least Preferred)
A				
B				
C				
D				

11. **Describe the rationale behind your ranking:** *

Question 6 - Sound sensor

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



12. **Please rank the following interaction styles in order of preference for a sound sensor (i.e. sound detector).** *

Mark only one oval per row.

	1 (Most Preferred)	2	3	4 (Least Preferred)
A	⬭	⬭	⬭	⬭
B	⬭	⬭	⬭	⬭
C	⬭	⬭	⬭	⬭
D	⬭	⬭	⬭	⬭

13. **Describe the rationale behind your ranking:** *

____

____

____

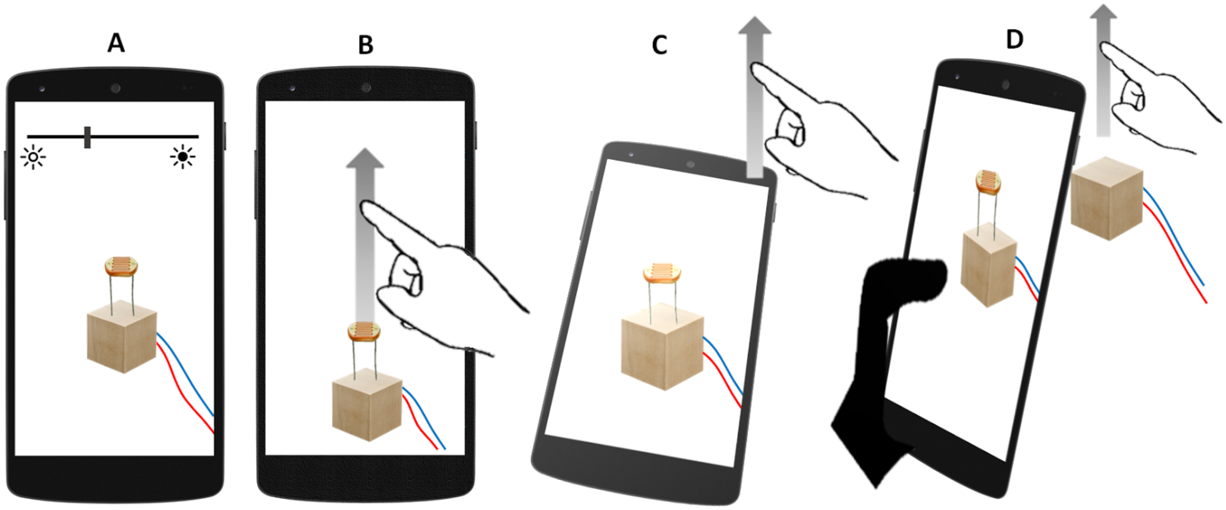
____

____

Question 7 - Biometric sensors

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



14. **Please rank the following interaction styles in order of preference for biometric sensors (e.g. heart rate, pH, pulse, muscle).** *
Mark only one oval per row.

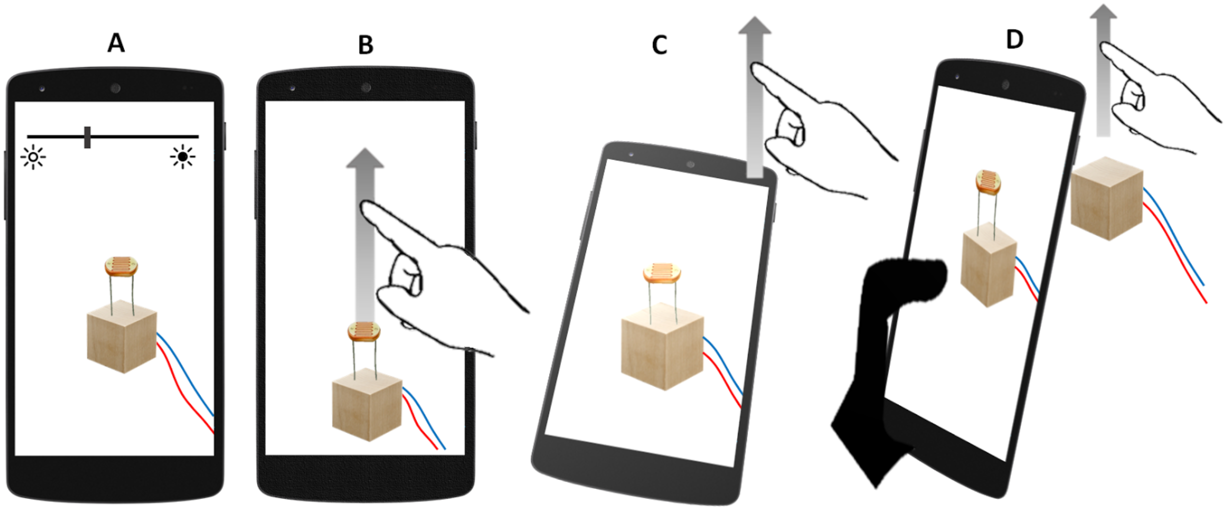
	1 (Most Preferred)	2	3	4 (Least Preferred)
A	◯	◯	◯	◯
B	◯	◯	◯	◯
C	◯	◯	◯	◯
D	◯	◯	◯	◯

15. **Describe the rationale behind your ranking:** *

Question 8 - Encoders

Please refer to the figure below when referring to the questionnaire.

Interaction Styles for Polymorphic Cube



16. **Please rank the following interaction styles in order of preference for encoders (e.g. rotary encoders, linear encoders).** *
Mark only one oval per row.

	1 (Most Preferred)	2	3	4
A				
B				
C				
D				

17. **Describe the rationale behind your ranking:** *

Additional Comments

18. **Is there anything else you'd like to add?**

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C.2 SAMPLE CODE

We include the complete set of sample code to provide additional details about the code provided in the studies.

```
Program the polymorphic cube component as follows:

1. LED

void loop()
{
// if Led should be HIGH
Serial.println(   1   );
delay(100);

//if Led should be LOW
Serial.println(   0   );
delay(100);
}

2. Servo

void loop()
{
// if clockwise
for(int pos=0; pos<=180; pos+=1)
{
```

```
        Serial.println(pos);
        delay(100);
}

//if counter-clockwise
for(int pos=180; pos>=0; pos-=1)
{
        Serial.println(pos);
        delay(100);
}
}

3. Pushbutton

char  ch;
void loop()
{
if(Serial.available()>0)
 {
   ch = Serial.read();
   if(ch==   1   )
   {
        // button is pressed, do something
   }
    if(ch==   0   )
    {
```

```
    //button is not pressed, do something
    }
  }
}

4. Photocell

char  ch;
void loop()
{
if(Serial.available()>0)
   {
    ch = Serial.read();
    if(ch==   1   )
    {
        // photocell is uncovered, do something
    }
    if(ch==   0   )
    {
        // photocell is covered, do something
    }
   }
}
```

```
Sample Arduino code for physical components:


1. LED
```

```
int ledPin = ; // assign pin number
void setup()
{
        pinMode(ledPin, OUTPUT);
}
void loop()
{
        digitalWrite(ledPin, HIGH); //to turn on LED
    digitalWrite(ledPin, LOW); // to turn off LED
}



2. Pushbutton

int buttonPin = ; // assign pin number
int buttonReading=0;
void setup()
{
        pinMode(buttonPin, INPUT);
}
void loop()
{

        buttonReading = digitalRead(buttonPin);
        if(buttonReading==1) // button not pressed
```

```
        {
                //do something
        }
    if(buttonReading==0) // button pressed
        {
                //do something
        }
}

3. Servo

#include<Servo.h>
Servo myservo;
int servoPin = ; //assign pin
int pos=0;
void setup()
{
        myservo.attach(servoPin);
}
void loop()
{
        //clockwise rotation
        for(pos=0; pos<=180; pos+=1)
        {
                myservo.write(pos);
                delay(20);
```

```
        }

        // counter-clockwise
        for(pos=180; pos>=0; pos-=1)
        {
                myservo.write(pos);
                delay(20);
        }
}

4. Photocell

int photocellPin = ; // assign pin number; photocell is an analog
int photocellReading=0;
void setup()
{
        pinMode(photocellPin, INPUT);
}
void loop()
{
        photocellReading = analogRead(photocellPin);
        if(photocellReading < 100) // if dark
        {
                //do something
        }
        // if light
```

```
    else
        {
                //do something
        }
}
```

C.3 SCENARIOS FOR DEVELOPING AR-MEDIATED PROTOTYPING VISION

To develop our vision for technology for AR-mediated prototyping, we first made a list of possible scenarios of people's interaction with such a tool. Based on these scenarios, we came up with a list of higher-level themes (physical and virtual form, circuitry and programming, physical interactions, social interactions), and list of possible tasks for technology for AR-mediated prototyping (discussed in Chapter 5). We include the seven scenarios for reference.

Scenario 1: AR Input - Single Digital Component

Gowri is building a simple music box. Every time Gowri interacts with the music box, a new song is played. To begin prototyping this idea, Gowri decides that she will have a button on a music box with a speaker. Each time she presses the button, the music box will play a new song.

Gather Components	Gowri needs a pushbutton and a mini speaker to build the music box. Gowri has a mini speaker, but does not have a pushbutton. She decides to use the AR mediated prototyping tool to simulate the missing pushbutton.
Build AR component	Gowri decides to use a small plastic box to be a placeholder for her missing pushbutton. She sticks the special AR tag on the top face of the plastic box.
Map Component	Gowri uses her smartphone app to assign the AR component to a pushbutton. After assignment, Gowri can see an AR pushbutton on her smartphone display.
Build Circuit	Gowri begins to build her physical circuit using an Arduino, a breadboard, mini speaker, and the AR pushbutton. She connects the mini speaker to pin 9 on the Arduino using wires. To connect the AR component to the physical circuit, Gowri first attaches wires to the header pins on the sides of the AR tag. Using those wires, she connects the AR component to pin 8 on the Arduino.
Write Code	Gowri programs her circuit using the Arduino IDE: each time the button is pressed, the mini speaker plays a new song.
Test Circuit	To test the functional behavior of the simple music box, Gowri begins to interact with the AR pushbutton. She holds her phone in front of the plastic box, and can see the virtual button. She presses the virtual button on the screen using touch and can hear a song begin to play. She presses the virtual button again, and can hear a new song being played.

Scenario 2: AR Input - Single Analog Component

Motivated by the successful music box prototyping, Gowri plans to re-iterate her design. This time, Gowri wants to build a musical instrument. Gowri wants her musical instrument to play back different tones based on different color inputs. To prototype this idea Gowri needs a color sensor and a mini speaker. Yet again, Gowri has a mini speaker, but is missing a color sensor. She decides to simulate the missing color sensor using the AR prototyping tool.

Map Component	Gowri decides to use her previously built AR component and reassign the mapped component. Gowri uses her smartphone app and reassigns the AR component to a color sensor. After assignment, Gowri can see an AR color sensor on her smartphone display.
Build Circuit	Gowri first changes the wiring for the color sensor component. Next, using the physical wires, she connects the AR color sensor component to pin A0 on the Arduino.
Write Code	Gowri writes a new Arduino program: each time red, green, or blue color is recognized, the mini speaker plays a different tone.

Test Circuit	To test the functional behavior of the musical instrument, Gowri begins to interact with the AR color sensor. She places her phone on a phone stand and positions it in front of the AR component such that the color sensor is visible on the phone display. Next, Gowri brings a red color LEGO block in front of her virtual sensor. The sensor detects red color and plays back a new tone. She repeats the test with blue and green colored LEGO blocks and hears unique tone for each unique colored LEGO block.

Scenario 3: AR Output - Single Digital Output Component
After her two successful prototypes, Gowri has many new ideas she wants to explore. First, Gowri decides to modify her earlier music box prototype. Gowri decides that it would be useful to get some visual feedback of when the music changes. For this iteration, Gowri decides that she will have a music stream as input for the music box, and each time the music changes, she wants to light up an LED to signal end of previous song and start of new song. For this iteration, Gowri needs an LED and a mini speaker. She has a mini speaker and decides to simulate the LED component.

Map Component	Gowri reassigns her previously constructed AR component to a green colored LED.
Build Circuit	Gowri re-wires her AR component and connects the component to pin 8 on the Arduino.
Write Code	Gowri writes a new Arduino program: each time a song ends, the LED turns on. When the new song begins to play, the LED turns off.
Test Circuit	To test the functional behavior of the music, Gowri positions the phone in front of the AR component such that the LED is visible on the phone display. Next, Gowri begins the music stream. Every time a song ends, Gowri sees her virtual LED turn on. The virtual LED turns off when the next song begins.

Scenario 4: AR Output – Single Analog Output Component
Based on the previous prototype Gowri thinks that instead of an LED feedback, she would like a livelier feedback. Gowri decides to replace the LED with a servomotor. She decides that every time a song ends, the servomotor will turn clockwise and hit a gong. When the new song begins, the servo will reset itself to the original position. For this iteration, Gowri has a mini speaker, but does not have a servomotor. Gowri also has a real gong.

Map Component	Gowri reassigns the AR component to a servomotor.
Draw Attachments	The smartphone app allows people to draw objects that can be attached to the virtual component. Because the servomotor is virtual, Gowri sees that she has the option to draw virtual attachments that fit on the servomotor. For this scenario, Gowri draws a mallet and attaches it to the servomotor wings.
Build Circuit	Gowri re-wires her AR component and connects the servomotor to analog pin A0 on the Arduino.

Write Code	Gowri writes a new Arduino program: each time a song ends, the servo rotates 180^0 and hits a gong. When the new song begins to play, the servo resets.
Test Circuit	To test the modified music box, Gowri positions the phone in front of the AR component and sees the virtual servomotor on the phone display. Next, Gowri begins the music stream. Every time a song ends, Gowri sees her virtual servomotor rotate clockwise. The prototyping app's simulation system automatically programs movement of attached objects. Therefore, Gowri also sees the attached virtual mallet moving similar to real world objects. Based on virtual mallet movement, Gowri knows when to hit the physical gong. When a new song begins, the servo resets itself.

Scenario 5: AR Input and Output – Multiple Components

Based on the success of her previous prototype Gowri decides to perform one last iteration. She decides to include two buttons to play and pause song streaming. Gowri does not have immediate access to two buttons.

Build AR component	Gowri decides to use two small physical buttons as placeholders for the missing pushbutton components. She sticks the special AR tag on the top face of each of the physical buttons.
Map Component	Gowri assigns the two newly created AR components to pushbuttons.
Build Circuit	Gowri wires her two new AR components and connects them to pin 1 and 2 on the Arduino.
Write Code	Gowri modifies her previous Arduino program to include the following: when the first button is pressed the music box begins to stream, when the second button is pressed the music stream is paused.
Test Circuit	To test the modified music box, Gowri positions the phone in front of the three AR component. She realizes that she either has to change the orientation of the phone to ensure all three components are visible, or move her phone further away from the AR components. Gowri decides to position her phone horizontally. To test the prototype, first, Gowri presses the play virtual button. The music stream begins. When the song ends, Gowri sees the virtual servomotor and the attached mallet rotate. Based on the virtual servomotor movement, she hits the physical gong. When a new song begins, the servomotor is reset. During the new song, Gowri presses the pause virtual button. The music stream is paused.

Scenario 6: Sharing AR Components

Gowri is very happy with her AR-mediated prototyping efforts and tells her sister, Sowmya about the music box project. Sowmya is excited to hear about the project and wants to rebuild the same musical instrument for herself. To help Sowmya build a replica of the music box prototype, Gowri offers to share her prototype design, and relevant code and virtual components with Sowmya.

Build AR component	Based on the prototype designs provided by Gowri, Sowmya rebuilds the physical prototype and three AR component placeholders.

Map Component	Sowmya searches through the shared library, and downloads and maps her AR components to Gowri's virtual servomotor, and two pushbuttons.
Build Circuit	Based on Gowri's instruction, Sowmya connects the servomotor component to pin A0, and the pushbuttons to pin 1 and 2 on the Arduino.
Write Code	Sowmya downloads the Arduino code Gowri shared, and uploads it to her local Arduino.
Test Circuit	Finally, Sowmya tests the music box prototype. She first, presses the play virtual button. The music stream begins. When the song ends, Sowmya sees the virtual servomotor and the attached mallet rotate. Based on the virtual servomotor movement, she hits the physical gong. When a new song begins, the servomotor is reset. Next, Sowmya presses the pause virtual button and finds that the music stream is paused.

Scenario 7: Switching to Real Components

Sowmya is very excited with the AR-mediated music box prototype she built. Happy with the function of the music box, Sowmya decides to switch the virtual components with real components and explore embodiment and form for her project.

Gather Components	Sowmya gathers the two pushbuttons and servomotor to switch with the AR components.
Switch Components	Sowmya replaces each virtual component one at a time. Since the wiring for the AR components was the same as the real components, Sowmya easily replaces the AR components with the real components. She also attaches a physical mallet to the real servomotor component.
Build Circuit	Because the circuit was previously constructed physically, Sowmya can retain her current circuit without any changes.
Write Code	Similar to circuit, because the code was written using the Arduino IDE, Sowmya does not have to alter code.
Test Circuit	Finally, Sowmya tests her physical computing music box project with real components and finds it to be working similar to the prototype version.
Embodiment and Form	Based on the functional success, Sowmya spends time in polishing her prototype by designing form and embodiment for the music box.

D

EARLY EXPLORATIONS

In addition to the projects discussed in this dissertation, we worked on two exploratory projects. While these projects were not focused on exploring *making within constraints*, we learned valuable lessons from them.

D.1 BUILDING SIMPLE PHYSICAL COMPUTING PROJECTS

To familiarize ourselves with programmable electronics, we experimented over three months with a range of materials for making including conductive tape, conductive ink, LED displays, servomotors, and temperature sensor among others. We built several simple self-directed projects to learn about circuitry and programming electronics (Figure 56). For example, to learn about temperature sensors and built in microcontroller Wi-Fi modules, we built what we called a "tea time notifier" system. The goal of the project was to notify a co-located friend about a social "tea time" event based on a physical action (pouring of water) (see Figure 56g). To implement this project, we built a circuit using a temperature sensor and conductive tape, and attached the temperature sensor to a mug object. On the software side, we wrote a Processing client-server program, which would send an image-based notification to a co-located person over Wi-Fi, when the temperature sensor readings reached a threshold value.

As part of building these projects, we learned two simple lessons. First, we always faced a scenario where we did not have immediate access to a required electronic component. When working on these projects, we spent significant time preparing a shopping list, based on projects we found on online tutorials. However, when it came to experimentation, and we wanted to try new ideas beyond those suggested by the tutorials, we often found that we needed new components and usually ordered the missing components from an online store. However, occasionally, we decided to purchase the components from a local store to get the components sooner (within 24 hours as opposed to waiting 2 days). While we were not severely resource-constrained, we had a limited research budget for purchasing electronics, therefore, restricting us from purchasing abundant resources in advance.

The second lesson learned was that there was a learning curve associated with building physical computing projects. While we found some projects easy to build (e.g., conductive tape, LED, and servomotor), we struggled with the circuitry of others (e.g., bubble display) for multiple reasons. For example, while using conductive paint was easy, understanding the relationship between the thickness of the paint and its resultant resistance took several trial and errors explorations. In some other cases, we spent significant time learning to interpret circuit diagrams. Although we had access to online tutorials and peers who could help us with circuitry problems, the process of building physical computing projects required us to spend long hours experimenting.

Our lessons learned are simple and not surprising (specifically being novice makers). However, they re-confirm that making-centered activities are not as easy and accessible to diverse groups of people as often proposed in the narratives of the Maker Movement.

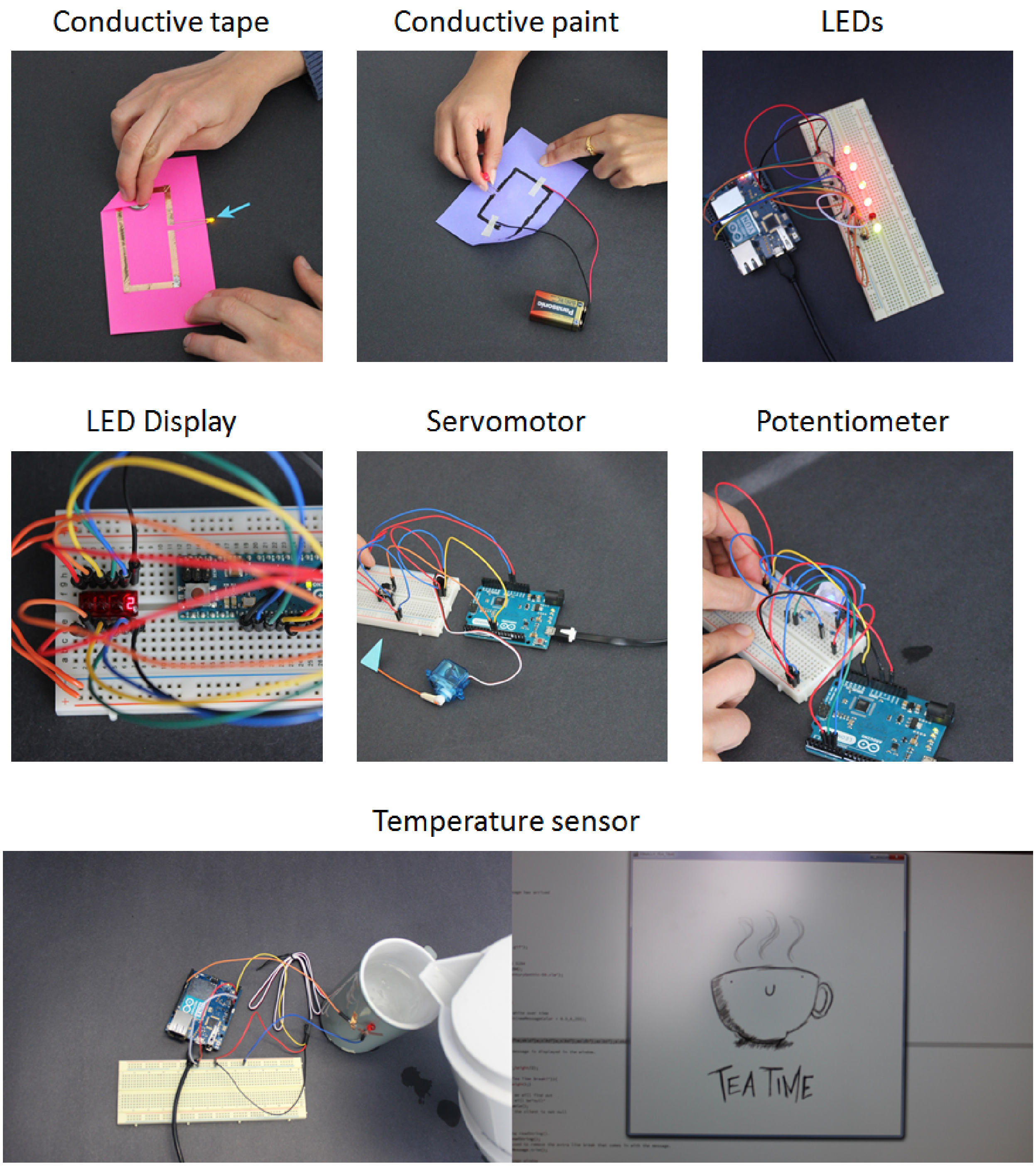

Figure 56: Simple physical computing projects developed to experiment with electronic components: (a) conductive tape-based LED circuit, (b) conductive paint-based LED circuit, (c) number input-based LED display, (d) timer display, (e) flag display, (f) potentiometer controlled LED lamp, (g) temperature sensor-based tea time notifier.

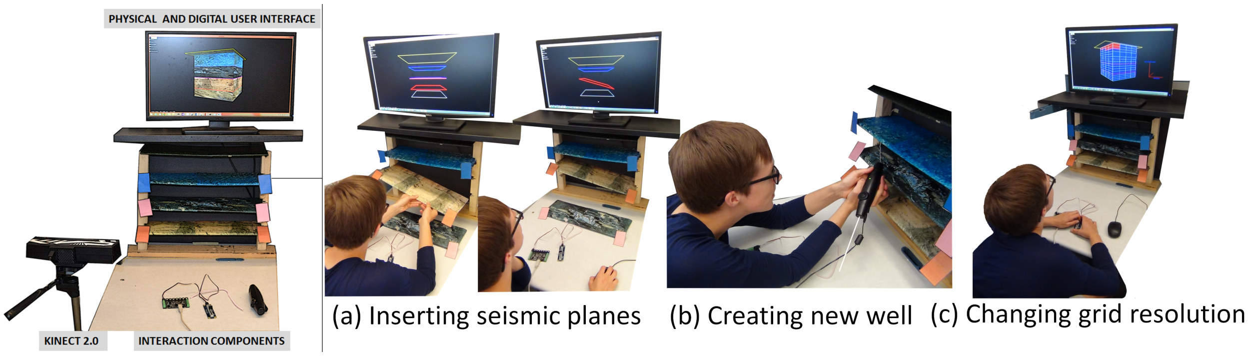

Figure 57: ReservoirBench system (Somanath et al., 2015b)

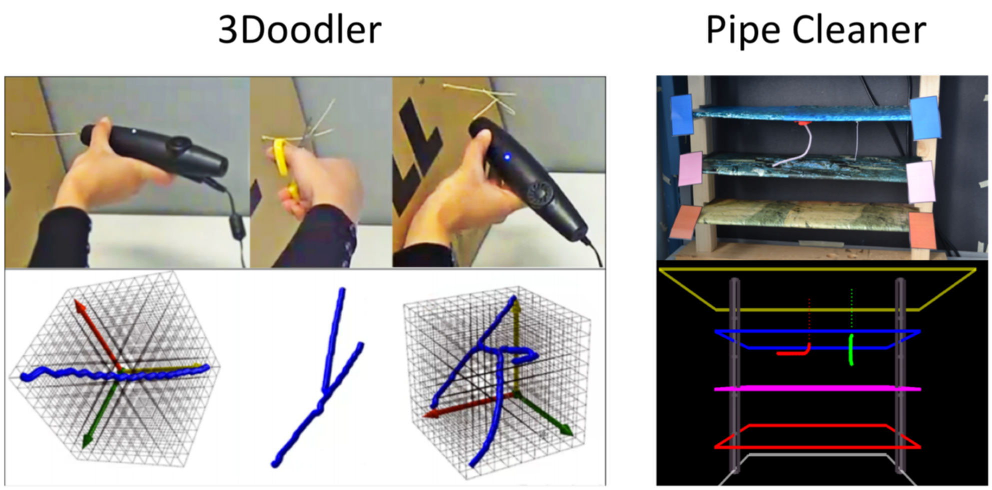

Figure 58: Creating well trajectories using: (a) 3Doodler (Somanath et al., 2014) and (b) pipecleaners (Somanath et al., 2015b)

D.2 RESERVOIRBENCH

ReservoirBench is an interactive workbench for educational geological science and engineering tasks (Somanath et al., 2015b). ReservoirBench represents an example of making using non-electronics materials. In this project, we used 3Ddoodler, a hand-held 3D printing tool, and pipe cleaners to create physical oil well trajectories.

We designed ReservoirBench to facilitate the education of novice audiences to teach them basic concepts of reservoir modeling and simulation workflow. Traditional training using lectures and software practice can lead to information overload, and retainability is questionable. As an alternative, we developed a physical workbench that is coupled with digital augmentation for learning. Our design takes advantage of the crucial role that spatiality and 3D representations play in petroleum reservoir modeling and allow basic domain concepts to be introduced and explored in a tangible and experiential manner (Figure 57).

Apart from interacting with static physical objects, learners working with the ReservoirBench can create physical well trajectories using 3Doodler (Figure 58a), and pipe cleaners (Figure 58b). One of the fundamental constraints to input well trajectories is that the material should have the ability to retain shape and yet be malleable. Pipe cleaners are advantageous as they are flexible and afford for molding, but are limited as they do not afford the property to be easily molded back to their original state. In contrast, 3Doodler is a step forward towards supporting free-form sketching of 3D objects and thus, can better support quick iterative design explorations.

Specific to using materials for making in user interfaces, we learned that the choice of materials has to be relevant to the application needs. Due to the meticulous nature of tasks conducted by reservoir engineers, creating well trajectories using 3Doodler and pipe cleaner is limited in terms of accuracy and precision that can be achieved. In the future, interaction designers interested in developing applications that help people create artifacts by themselves should focus on exploring the role of materials for making in interface design.

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