ReConstructibles: Physically Reconfigurable Shape-Changing Interfaces

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Dedicated to Sara

Abstract

Most widely used devices have a single display which cannot adapt to specific content or applications. A "cell-composed" device is an alternative to static, flat displays. It decomposes the display into a system of multiple smaller touchscreen devices. The fundamental strength of this interface is it can be subdivided into smaller devices and cells can be rearranged into new devices. We propose the term *reconstructibility* to describe cell-composed devices. This term emphasizes the ability of the user to construct, deconstruct, and reconstruct devices from cells.

We further introduce the ReConstructibles research vision for cell-composed devices. Any ReConstructible device can be subdivided into multiple devices or reconfigured to provide the user with new functionality.

This project contributes a deeper understanding of the user experience with ReConstructibles through several user studies. First, we conducted design workshops, which gave insights into potential application domains for ReConstructibles and how device size affects the user experience. Second, we ran a week-long deployment with low-fidelity prototypes, which increased our understanding of user perspectives on cell-composed devices and narrowed our search for application domains. After several months developing high-fidelity prototypes, we conducted a second deployment study, this time with functioning devices. Deployment studies are extremely rare in SCI research, but offer invaluable insights. In this final study, participants reported receiving real benefits to their workflow and productivity. This is evidence supporting several potential application domains for ReConstructibles.

We present ReConstructibles as a hardware and software toolkit for research in cell-composed devices. We provide detailed documentation, 3D model files, code listings, and instructions for other researchers to replicate and expand upon our work.

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Several others in the Computational Foundry gave excellent advice and support. Shane Fleming suggested using the TinyPICO Nano board in our prototypes, which gave us the functionality and size we wanted. He also taught me the challenges of inter-device communication and embedded programming. Anna Carter gave me expert advice on writing a research paper and running user studies. I spent most of my time in the Maker Lab on the ground floor. There, Kris Seunarine and Gavin Bailey helped me resolve all sorts of odd hardware-development problems, from testing components to 3D printing. Sam Oliver and Kira Pugh were invaluable as my extra pair of hands. They made assembling and soldering these small devices so much easier.

Finally, a big thanks to my family. My wife, Sara, for being a fantastic cheerleader and editor. My son, Theodore, for showing me cool rocks.

Contents

Chapter 1

Introduction

Most widely used devices have a single display. Smartphones, watches, personal computers, and tablets run countless applications, but their dimensions remain fixed. This limits the device's overall usability, since the display itself cannot adapt to specific content or applications. Work on removing this limitation has produced innovations such as foldable displays[1], but ultimately our interactions with computing devices are limited to rectangular touchscreen displays.

In 2019, the PickCells project [1] designed an alternative to static, flat displays by decomposing the display into a system of multiple smaller touchscreen devices. Each PickCells device, called a cell, had two modes of operation. First, a cell operated individually, communicating with other PickCells via WiFi. Second, PickCells connected together magnetically to form a larger device. And since groups of PickCells could be separated and recombined in arbitrary arrangements, the resulting concept was fully reconfigurable. Like working with Lego bricks, users would construct from PickCells new devices that fit their needs.

PickCells built on a wide body of research in reconfigurable cube-like devices. Sifteo Cubes [2] were fully reconfigurable computers that could coordinate complex applications, but had no mechanism for physically attaching cubes together. Robot Pebbles [3] were extremely small cubes capable of creating complex 2D configurations through self-disassembly. Blinky Blocks [4] were programmable blocks that could be stacked or magnetically connected to form 3D structures. These projects together with PickCells demonstrated the fundamental strength of cell-composed devices: devices can

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[1] E.g., the Samsung Galaxy Fold3: https://www.samsung.com/uk/smartphones/galaxy-z-fold3-5g/

be subdivided into smaller devices and cells can be rearranged into new devices. In this project, we take inspiration from the history of cell-composed devices to create a new research vision and interface.

1.1 ReConstructibles Research Vision

We propose the term *reconstructibility* to describe cell-composed devices:

> A *reconstructible* device is *tearable*—cells easily separate and function independently—and fully *reconfigurable*—cells can be physically connected in an arbitrary manner.

We call this *reconstructibility* to emphasize the ability of the user to construct, deconstruct, and reconstruct devices from cells. *Reconstructible* devices are highly reconfigurable, meaning they can perform a wide range of applications.

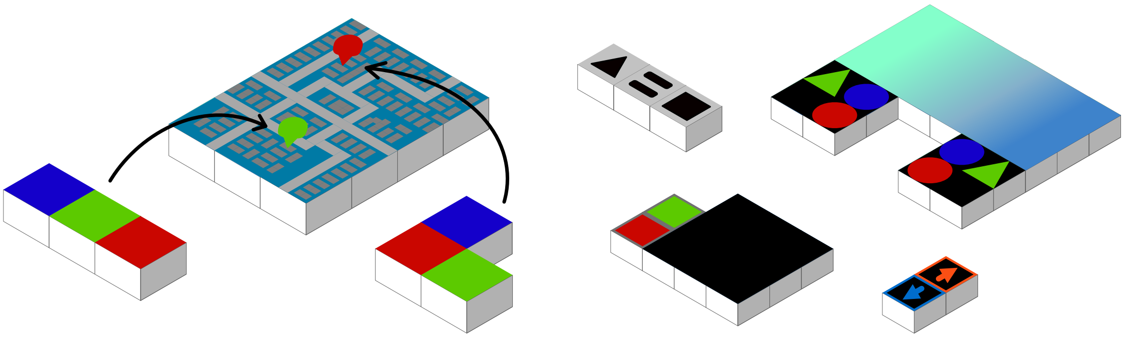
To unify research into this powerful class of shape-changing interfaces, we introduce the ReConstructibles research vision for cell-composed devices. Each ReConstructible device is called a 'cell', 'cube', or 'block'. ReConstructibles can be magnetically connected along both horizontal axes. ReConstructibles operate individually via wireless communication and collectively when physically connected.

When connected, ReConstructibles form a seamless touch-screen experience. Each ReConstructible features a wide variety of functions and technologies, including gesture recognition and GPS positioning. Users connect and disconnect cells with natural motions, creating shapes informed by specific applications, such as those described in the following example application scenarios (illustrated in Fig. 1.1):

Scenario 1: Sharing ReConstructibles with Children. *Michael doesn't want to buy smartphone for his children, but he wants to communicate with them. He gives each child three ReConstructibles when they leave the house. To request a lift home, the child arranges the ReConstructibles into a specific configuration (Fig. 1.1a). This triggers an alert on Michael's ReConstructible device and displays a GPS pin of his child's location. If the situation is dangerous or urgent, the child forms a different configuration, triggering an urgent alert on Michael's ReConstructibles. If Michael doesn't respond quickly, ReConstructibles notifies local law enforcement.*

Scenario 2: Customized Controllers. *Katherine recently downloaded a new game to her ReConstructibles. While on break at work, she forms a game controller to play it (Fig. 1.1b). When it's time to get back on task, Katherine creates a computer mouse from her cubes. During her afternoon presentation, she uses two ReConstructibles as forward and backward buttons to control her slides. At home, she arranges her ReConstructibles into a TV remote and sits on the sofa to enjoy her favorite show.*

These example scenarios highlight the benefits of *reconstructibility*. Any ReConstructible device can be subdivided into multiple devices. This empowers users to share their devices or to perform different functions simultaneously. ReConstructibles can also be reconfigured for new functionality. Users rearrange cubes to design a device with the correct affordances for a particular application. This flexibility for users is key to ReConstructibles' utility.



a) Scenario 1: Sharing ReConstructibles with Children

b) Scenario 2: Customized Controllers

Figure 1.1: Example Use-Case Scenarios. (a) **Scenario 1: Sharing ReConstructibles with Children.** To request a lift home, the child arranges the ReConstructibles into a specific configuration (Fig. 1.1a). This triggers an alert on Michael's ReConstructible device and displays a GPS pin of his child's location. If the situation is dangerous or urgent, the child forms a different configuration, triggering an urgent alert on Michael's ReConstructibles.
(b) **Scenario 2: Customized Controllers.** Katherine can create four different devices from her ReConstructibles for specific activities: a game controller, a TV remote, forward and backward buttons to control her presentation slides, and a computer mouse.

1.2 Project Overview

The purpose of this project is to explore the user experience with ReConstructibles, develop robust prototypes, and define key application domains for ReConstructibles. The project evolved through user studies and prototype development.

We began with a design workshop, in which study participants generated application ideas for the scenarios described above (Section 1.1) and for new topic areas. Participants also evaluated the ideas they generated in a consistent way, which made it easier to compare and contrast their ideas. At this stage, trends in interaction behaviors and user-favored applications started to emerge.

Next, we conducted a deployment study with low-fidelity prototypes. Participants took home model ReConstructibles for a week and used them as props for creating new application ideas in the context of their daily lives. We wanted to see if they would validate the results of the workshop or head in different directions. Interaction patterns became more clearly defined and a few application domains rose to the top. In particular, participants most frequently imagined using ReConstructibles for three activities:

1. Managing tasks and errands with reminders and tangible list manipulation

2. Timing or counting down for everything from cooking to when to take out the rubbish bins

3. Displaying information, images, and animations in the background

These three activities were also frequently considered in the workshop, confirming those results and focusing our efforts and attention.

We created working prototype devices with compact cell size, strong magnetic connection mechanisms, and fast inter-cell communication protocols. To test these prototypes, we planned an "in-the-wild" deployment study. For this final study, we developed a simple software application for each of the three most common activities from the low-fidelity deployment to run on our prototype devices. These weren't flashy or novel applications, but straightforward and familiar. Most importantly, they were applications that our participants thought would be useful to them. Participants in the deployment used our devices for 2-3 days and reported on their experiences including the applications into their daily routine. Their responses were overwhelmingly positive. Participants reported that even the simple applications, particularly the task manager app, were genuinely beneficial.

Many studies have fascinating future-focused ideas about what shape-changing interfaces could accomplish. Unfortunately, these ideas are difficult to effectively evaluate, since they are so far beyond what we can currently build. Our evaluations focused on providing practical, tangible benefits to users with software and hardware we actually developed. Our design workshops and low- and high-fidelity prototype deployments demonstrate that simple, straightforward applications can have surprising utility in peoples' everyday lives. These studies helped us to identify task management, countdown timing, and ambient displays as valuable domains for ReConstructibles applications. Future work should explore these applications further.

Generally speaking, deployment studies are rare in SCI research, especially with working prototypes, due to the challenges associated with creating sufficiently robust prototypes for experimental interfaces. As far as we can tell, prior to this work, no such deployment has ever been conducted with cell-composed devices. While resource and time constraints prevented us from running a long-term deployment of working hardware with many participants, our short-term deployments with a small number of participants still gave us extraordinary insights into the user experience with this type of shape-change. Future work should build on our study designs to conduct more deployment studies, especially longer-term deployments of more robust working prototypes.

We present ReConstructibles as a hardware and software toolkit for research in cell-composed devices. Detailed documentation, 3D model files, code listings, and instructions can all be found on our GitHub repository, made freely available to other researchers interested in replicating and expanding upon our work. With these foundational tools, the SCI research community can make progress toward the ReConstructibles vision and further explore *reconstructible* computing interfaces.

Chapter 2

Background

Here we present a critical synthesis of research in shape-changing computer interfaces. We begin with a discussion of definitions and terminology (Section 2.1) to establish a consistent vocabulary for evaluating research, then we frame the project in the context of the broader challenges facing the SCI research community (Section 2.2). On that foundation, we turn to a more focused discussion of research work related to ReConstructibles (Section 2.3). Finally, we look at SCI research evaluation methodologies to inform this project's evaluation plans and user study designs (Section 2.4).

2.1 Definitions and Terminology

The field of shape-changing interfaces (SCI) covers a broad range of devices and problems. A comprehensive definition of SCI is provided by Alexander et al. [5]. Under their definition, SCIs:

1. Use physical change of shape or change in materiality as input/output
2. Are interactively and computationally controlled
3. Are self-actuated and/or user-actuated
4. Convey information, meaning, or affect

Building on this definition and Roudaut's previous shape-resolution taxonomy [6], Kim et al. [7] created a flexible taxonomy for defining specific SCIs. The taxonomy lists characteristics of an SCI's reconfigurability (See Table 2.1). Essentially, each property

Size	Granularity	Porosity
Curvature	Amplitude	Waviness
Closure	Stretchability	Strength
Speed	**Modularity**	

Table 2.1: List of SCI Features from the Morphees+ Taxonomy [7]. ReConstructibles belongs primarily to the *Size* and *Modularity* features.

describes a different way that an interface changes shape and provides a method of quantifying that change. Any SCI will change shape according to at least one property in the taxonomy. This is what makes the taxonomy so useful to researchers: it provides consistent tools for comparing and contrasting different interfaces' shape-changing behavior.

While the taxonomy describes how an particular interface changes shape, we need other terms to talk about how users interact with SCIs. Interactions can be classified across a continuum stretching from "directly-controlled" (fully user-initiated) interactions to "system-controlled" (fully device-initiated) interactions [7, 8]. Between these extremes lie *negotiated* and *indirectly-controlled* interactions which are primarily (though not exclusively) user-initiated or device-initiated, respectively.

These definitions and taxonomies provide a common vocabulary and evaluation criteria for organizing and clarifying the SCI research conversation. ReConstructibles belong primarily to the *Modularity* and *Size* taxonomy features. *Modularity*, because any number of cells can be separated and recombined, and *Size*, because these reconfigurations result in changes to the overall size of the final constructed device. Interactions with ReConstructibles are primarily *directly-controlled*, since the user must manually rearrange cells. However, some interactions will be *negotiated* interactions, where the system suggests or requires a specific arrangement before running a particular application.

Since *Modularity* encompasses a wide range of devices, we define the term *reconstructibility* to specifically describe modular interfaces that are *tearable* (easily divided into several smaller interfaces) and *connectable* (separate interfaces can be physically connected to form a single interface). Many existing devices have one or the other characteristic, but ReConstructibles combines both. We will also refer to a device's *reconfigurability*, or the ability of a device to perform more than one function. A high level of reconfigurability indicates a device can perform many functions, a low level of reconfigurability indicates a device can perform only one or few discrete functions.

2.2 Research Challenges

In 2018, twenty-five SCI experts identified twelve "grand challenges" for SCI research [5]. Broadly speaking, these challenges include technological concerns (e.g., scalability, robustness), societal concerns (e.g., sustainability, security), design concerns (e.g., applications, aesthetics), and user behavior concerns (e.g., replication, user experience). Below we discuss the specific grand challenges pertinent to ReConstructibles and analyze recent research work contributing to the resolution of these challenges.

2.2.1 Challenge 1: Applications for Shape-Changing Interfaces

The purposes and benefits of SCIs have been grouped into five general categories [5, 9]: **Adaptive Affordance**, **Augment Users**, **Simulate Objects**, **Communicate Information**, and **Hedonic and Symbolic Purposes**. However, the research community has so far been unable to firmly establish "killer applications" that will make the use of shape-change much more viable in the commercial sector. This is an important issue. A targeted application domain will make future research more focused and cohesive. And if shape-changing devices become part of mainstream technology use, related research will have more impact on real-world problems.

Lists of unique SCI applications have been compiled and analyzed [10, 11], many interesting prototypes have been developed (see Appendix A), but so far this challenge remains unresolved. This stems, in part, from the fact that the research community lacks solid, evidence-backed justification that SCIs are better than cheaper, less-complex alternatives [9].

As we developed and studied ReConstructibles, we sought to define and prove specific application domains for which cell-composed devices are uniquely designed. At the beginning of the project, the most promising possibilities included adjustable controllers (e.g., for video games, smart-home appliances, etc.); device sharing; and data sharing, visualization, and manipulation. Device sharing was of particular interest, because the easy subdivision of ReConstructibles opens up many possible sharing schemes, such as those described in the Make Yourself at Phone project [12]. However, our evaluations demonstrated that data sharing, visualization, and manipulation applications were the most popular among participants Section 3.3.

2.2.2 Challenge 2: Tools for Application Content Design

Related to the challenge of finding applications for SCIs is the challenge of designing content for these devices. Most research prototypes are not designed to be particularly robust. However, with the right resources, these devices could be prepared for commercial deployment. Unfortunately, most prototypes don't have accompanying toolkits for commercial content developers. Toolkits are challenging to create and expensive to maintain, but without these tools, shape-changing devices will likely remain in research laboratories and never move into real-world consumers' hands.

Some research has developed generalized toolkits, such as new languages for shape-changing displays [13] and the Morphino toolkit [14], but toolkits for specific devices often fall outside the scope and resources of research projects aimed at exploring concepts and designs.

As we developed and studied ReConstructibles, we sought to create tools for working with this platform. This included providing clear device and code documentation (e.g., schematics, component listings, 3D model CAD files, code listings, etc.), example applications, and content design principles. We stored this data in a GitHub repository. These lay the groundwork for further research and the eventual introduction of ReConstructibles into the commercial market. Future work should develop code libraries and frameworks to aid developers in creating ReConstructibles applications.

2.2.3 Challenge 3: Understanding the User-Experience

While specific user experiences with shape-change are often studied during the evaluation of particular prototypes [15, 16, 17, 18, 19, 1, 20], few studies attempt to understand the user-experience with shape-change more generally. We need more studies of how users perceive or interact with SCI [21].

Valuable insights have been drawn from focused examination of shape-changing buttons [22, 21]. Tiab et al. [21] determined that *perceived affordance* is a critical factor for SCI design. They used shape-change to signal affordance with buttons. Shape-changes that caused button movements conveyed cues about the state of the button (e.g., on/off), but did not reliably signal to the user how to interact with the button. Some of these sorts of signifiers were misinterpreted as do-not-touch warnings. Tiab et al. concluded that this incorrect perception stems from how affordance, system state, and state-change feedback are intertwined. When designing SCIs, the *perceived affordance* of the interface must be carefully considered to encourage the user to interact with it. The authors concluded that shape-change easily lends itself as an effective indicator of state, but we lack design principles for how to design shape-changing indicators of affordance [21].

Others have studied the techniques users employ to find information on non-rectangular displays [23], discovering that rectangular grids have the fastest search time, and that gaze patterns for non-rectangular grids follow a circular path. The way users talk about shape-changing devices can also be instructive, since they will often describe an artifact by talking about its "personality". They use terms such as "predictable", "territorial", and "playful" [24].

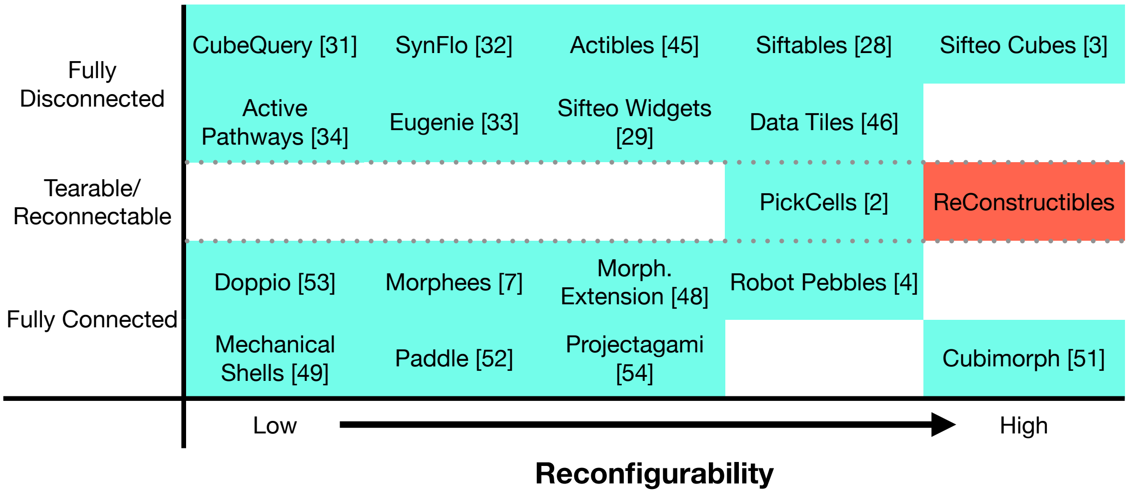
Part of the reason this challenge hasn't been fully resolved is few publications are replicated. From four major HCI publications and nearly 900 published papers, only 3% were replications of earlier work [25]. Replication is critical to strengthening or qualifying the validity of existing research, but most authors and journal editors prioritize novelty, thereby discouraging replications. We might encourage more replication by encouraging researchers who build on particular studies to replicate them as part of their expansion on the existing work.

The ReConstructibles project presents a rigorous study of *reconstructibility*, exploring the user experience through design workshops and deployment studies with low- and high-fidelity prototypes. Since the PickCells project introduced the first *reconstructible* interface to the SCI research community, replicating this work would validate a foundational research contribution relevant to our work. However, ReConstructibles differ considerably from PickCells, thereby rendering a one-to-one replication unproductive and impractical. Instead, we based our design workshops on the same dialogue-labs methodology [26] used by PickCells for their own workshop studies. By following a similar study methodology to generate new applications through design activities, our project was able to validate PickCells' results while expanding in new directions and contributing unique and significant findings. We then further examined the user experience with *reconstructibility* through deployment studies. A comprehensive discussion of our evaluation and results is provided in Chapters 3, 4 and 6.

2.3 Physically Reconfigurable Interfaces

With the proper research vocabulary and perspective, we now explore research work specifically in the realm of physically reconfigurable interfaces. These SCIs are the most relevant to ReConstructibles, because ReConstructibles are fully physically reconfigurable.

Fig. 2.1 displays the key prototypes described below in terms of their reconstructibility.



Fully Disconnected	CubeQuery [31]	SynFlo [32]	Actibles [45]	Siftables [28]	Sifteo Cubes [3]
	Active Pathways [34]	Eugenie [33]	Sifteo Widgets [29]	Data Tiles [46]	
Tearable/ Reconnectable				PickCells [2]	ReConstructibles
Fully Connected	Doppio [53]	Morphees [7]	Morph. Extension [48]	Robot Pebbles [4]	
	Mechanical Shells [49]	Paddle [52]	Projectagami [54]		Cubimorph [51]

Figure 2.1: Reconstructibility: Key research works are arranged in terms of their reconstructibility. Prototypes range from fully disconnected (no physical connection) to fully connected (no physical separation). Prototypes with low reconfigurability are able to perform only a few functions, while those with high reconfigurability are able to perform a wide range of different functions. PickCells and ReConstructibles are unique in sharing the properties of fully connected and fully disconnected prototypes. This is the primary reason these devices have such high reconfigurability. This chart also highlights the need for more research in this space.

2.3.1 Tearable Devices

One of the most reconfigurable fully-disconnected devices is the extensively studied Sifteo Cubes [2] which came out of the Siftables project [27]. A Sifteo Cube has a square touchscreen display and sensors to detect users gestures and the proximity of other Cubes. Cubes are *tearable*, they operate both individually and in conjunction with adjacent cubes. The resulting interface is very *modular*. However, since Sifteo Cubes have no *connectability*, it is unfeasible to use more than three Cubes as a single interface without the aid of a firm, flat surface, such as a table.

Sifteo Cubes were temporarily commercially available, which helps explain their frequent use by HCI researchers. Studies have used Sifteo Cubes to examine tangible controls for digital processes and information. Often this took the form of placing Cubes onto an interactive tabletop display and using them to control the display. [28, 29, 30, 31, 32, 33, 34, 35] are all studies of this nature. This approach represents the largest volume of Sifteo Cube research, but the Cubes have also been examined as stand-alone interfaces for interactive gaming [36, 37], personal data displays [38], and even tools for computer science education [39, 40]. These last two studies discovered that students had better retention of material and high excitement for learning when they could handle a physical manifestation of their coding efforts. As fascinating as these research studies are, taken as a whole these sorts of devices have received relatively narrow treatment.

[redacted]

a) Sifteo Cubes.

b) Cubimorph.

Figure 2.2: Images of highly reconfigurable shape-changing devices. (a) Sifteo Cubes running the Chroma Shuffle application [2]. Sifteo Cubes are an example of a fully-disconnected, highly reconfigurable device. (b) Cubimorph models (foreground) and prototypes (background) [41]. Cubimorph is an example of a fully-connected, highly reconfigurable device.

2.3.2 Devices as Tangible Controls

We note that we found a surprising amount of interest in tangible controls for tabletop displays while exploring research on physically reconfigurable interfaces. These include those mentioned above that used Sifteo Cubes [28, 29, 30, 31, 32, 33, 34, 35], but also Spare Tangibles [42, 43, 44], Actibles [45] (essentially circular Sifteo Cubes), DataTiles [46], and SLAP Widgets [47]. Most research using Sifteo Cubes explored the use of individual cubes, not the interactions between cubes. We believe the application space for these sort of interfaces to be much broader than this. For example, the PickCells project described a large design space that included applications such as tangible passwords, security keys, break-off controls, remote sensors, screen sharing, smart-home control, trip planning, crowd contributions, and more.

Existing research clearly shows that when operated individually multiple small devices can be used for a variety of data manipulation and control scenarios. The design space of ReConstructibles encompasses all of these applications, but further includes widgets that change size (cells connect together), are not restricted to table-top use (magnetic connections hold in free space and cubes can be attached to magnetic surfaces), and physically repurposable (individual cells are reconfigurable for entirely different applications).

2.3.3 Connectable Devices

Several researchers have developed interfaces that are *modular* and *connectable*, but not *tearable*. Blinky Blocks [4] are LEGO-like programmable blocks that can be stacked or magnetically joined to create arbitrary shapes. Each block has RGB LEDs, an onboard microphone and speaker, and impulse sensors to detect shakes and taps. Blocks can detect their neighbors and learn the arrangement of the entire system. The authors developed a distributed programming algorithm for configuring a variety of applications, where the user simply needs to rearrange the blocks to run a new application. However, Blinky Blocks must share a power source, which prevents them from being used individually.

Like Blinky Blocks, Robot Pebbles [3], the Morphology Extension Kit [48], Mechanical Shells [49], and Topobo [50] are all *modular* and *connectable*. Devices are composed of several smaller pieces working together. The individual pieces can be rearranged, removed, or replaced by new components to modify the behavior of the system. The interfaces are effective tools for reconfigurable applications [4, 3, 48], adaptive affordance [49] and child education [50].

These three devices come close to being fully *reconstructible*, since individual parts can be separated and rearranged for new functionality. However, each piece does not operate independently, so the full system isn't truly *tearable*. The device functions only as a connected system. This is the key characteristic of ReConstructibles: cells can cooperate to form a cohesive system, but also function just as well individually or even as multiple smaller devices composed of only a few cells.

Many physically reconfigurable devices are either *tearable* or *connectable*, but ReConstructibles unifies both characteristics into a uniquely powerful, modular interface.

2.3.4 Inseparable Devices

Cubimorph [41] is a concept prototype that closely resembles the vision of the ReConstructibles project. Cubimorph is designed to be nearly fully reconfigurable, with individual cells turning on hinges. This allows for easy physical manipulation of the system into a form factor that suits a given application. This device is very *modular*. Unlike ReConstructibles, however, Cubimorph has no *tearability*. Cubes cannot be separated, ultimately limiting the possible reconfiguration space.

Like Cubimorph [41], Paddle [51], Doppio [52], Projectagami [53], and Morphees [6] are all interfaces with a high degree of modular reconfigurability, but no *tearability*. None of these prototypes can be separated into independently functioning interfaces. They provide valuable insights into the applications and key affordances of physically reconfigurable SCIs, but they lack the level of application variety provided by *reconstructible* interfaces.

2.4 Evaluation Methods for Tangible Devices

SCI researchers employ a variety of methodologies for evaluating their work. Exploring the approaches taken by other researchers helped us craft our strategy for evaluating this project. We focus our attention on evaluations of physically reconfigurable interfaces, since these are most closely related to ReConstructibles.

Methodologies are grouped into four categories: design workshops, informal evaluations, technical evaluations, and controlled experiments. While each method category is discussed individually below, we note that many research projects employed more than one methodology. For example, the ShapeCanvas project [54] involved a controlled experiment (discussed in Section 2.4.4) followed by a brief design workshop (discussed in Section 2.4.1).

Combining multiple methodologies gave researchers a more well-rounded evaluation of their project. Consequently, the ReConstructibles project will be evaluated using several methodologies.

2.4.1 Design Workshops

Design workshops are a common approach to SCI user studies and are often conducted early in the research process, when prototypes haven't been fully designed or developed. By encouraging non-academic users to imagine applications or interactions for a new SCI, researchers are able to expand the design space beyond what would be possible on their own. The results of design workshops guide the development of prototypes and SCI applications. This methodology is particularly effective at establishing the design space of a new SCI.

Generally, design workshops are divided into three phases: demonstration, training, and design. During the demonstration phase, participants are introduced to the prototype or concept and shown some application scenarios or problem sets to get their creative juices flowing. For example, the Tilt Display [55] design workshop presented to participants seven applications that demonstrated the range of Tilt Display capabilities, including fixed modeling, movement, and video display. In the training phase, they are instructed on the design tools available to them (e.g., sticky notes, whiteboards, etc.) and taught how to use prototypes, if a prototype is provided. For example, the Ripple Thermostat project [19] helped participants familiarize themselves with the device, by taking them through a few example scenarios and device behaviors. The design phase involves brainstorming ideas, verbally or on paper, and may be followed by an user evaluation of the ideas generated.

Workshops usually place participants into co-design groups [1, 55, 22, 19, 12, 52, 10, 14], but participants may also work alone [56, 54, 35]. Often, exploratory studies to get initial impressions of a particular interface operate very similarly to a design workshop [23, 52, 55].

2.4.2 Informal Evaluations

Informal evaluations are primarily helpful for adjusting the course of a particular project, because the results of informal evaluations do not provide a solid foundation for validating a design or expanding the application space. Informal evaluations generally fall into one of two categories: informal feedback and self-evaluation.

2.4.2.1 Informal Feedback

Researchers may solicit informal feedback when they want user perspectives, but don't have the time or resources for a full participant study. Researchers might seek informal feedback after a demonstration of the prototype [46, 53] or at the end of a controlled experiment [17] or design workshop [56]. When the prototype is designed for a highly specialized application, feedback from subject-matter experts may be more valuable [42, 43, 44]. Feedback is obtained through open-ended questionnaires, recorded videos of user responses, or discussions with participants as they interact with the prototype.

Informal feedback helps researchers refine existing projects and plan new ones. It might even provide anecdotal evidence to support conclusions drawn from controlled experiments and design workshops. However, informal feedback data does not generalize and should not be used as the primary evidence for drawing conclusions about SCI research results. For example, after a demonstration of Projectagami prototypes [53], informal feedback indicated the usefulness of a device that represents intuitive physical shape-changing objects, but also the difficulty of discovering possible transitions without a demo. This inspired the authors to consider new ways of indicating instructions for folding operations. However, the informal feedback provides no solid conclusions about the effectiveness of folding shape-changing interfaces.

2.4.2.2 Self-Evaluation

Researchers choose to self-evaluate when a participant study is infeasible (either due to resource constraints or insufficiently developed prototypes) and when a prototype does not benefit from thorough technical analysis. Self-evaluations involve a discussion of project theory, applications, and design that is not based on results from another evaluation, such as a controlled experiment. When self-evaluating, researchers may discuss the strength of their prototype designs [15, 27, 41], the applications envisioned by the authors for the project [30, 57, 18, 45], or how the authors perceived the suitability of their prototypes for those applications [49, 13].

In a few cases, self-evaluated studies include a secondary evaluation via informal feedback [53, 46, 42] or technical assessment [48, 58]. However, the majority of these studies were exclusively self-evaluated.

This evaluation methodology alone is insufficiently rigorous to fully validate and support research results. It is therefore useful for directing intermediate stages of project development or describing a research vision, but should not be relied upon as the primary evidence for general research conclusions. Strong conclusions are based on strong evaluations.

2.4.3 Technical Evaluations

Technical evaluations involve quantitative analysis of key prototype properties [52, 48]. For example, Suzuki et al. measured the speed, accuracy, and strength of their ShapeBots prototypes [58]. Technical evaluations assess the robustness of prototype design. They are helpful for understanding the strengths and limitations of prototypes and lend insights into how to refine a design.

Many projects conduct technical evaluations throughout prototype development, since detailed specifications are a natural product of device design and creation. These are generally not reported as evaluations, unless they are critical to achieving project objectives. Instead, technical evaluations often appear in SCI research work as descriptions of device design.

2.4.4 Controlled Experiments

Controlled experiments with participants are by far the most common methodology for evaluating prototypes. They involve assigning a set of conditions to each participant and measuring results consistently. Participant studies are critical to SCI research. When designing a new interface, researchers need to know how it will be received by users. The best way to get this information is directly from users.

In recent work, controlled experiments took one of three forms: task completion, configuration exposure, and application demonstrations.

In Task Completion studies, participants were assigned tasks to complete either by directly using the apparatus or with the apparatus in close proximity [38, 20, 23, 24, 32, 29, 37]. Researchers measured task completion time [17, 51, 36], device performance [52, 47], or users' perceptions of and experience with the shape-changing device [59, 33, 28, 34, 35]. This format was used primarily to evaluate the effectiveness of specific shape-changing interactions and devices.

In Configuration Exposure studies, participants were presented with a series of device configurations and behaviors [16]. Users then rated the appropriateness of combinations of various types of stimuli [22], measured the emotional effect of each behavior [19], or described their impressions of device affordance, system state, and feedback [21]. This format was used primarily to deepen understanding of the user experience with shape-change, not to validate the usefulness of a prototype.

In Application Demonstration studies, participants were shown several example applications of a shape-changing prototype [55, 54, 31]. Researchers conducted semi-structured interviews to collect data on user perceptions of the prototype generally and the demo application scenarios specifically. This format was used primarily to evaluate potential shape-change applications, but it also helped researchers evaluate their prototype designs.

Each experiment format can be conducted "in the wild", as demonstrated by [16, 54, 38]. Testing shape-changing prototypes outside of the laboratory gave researchers deeper insights into how shape-change would be received in the real world. For example, the coMotion project [16] placed a shape-changing bench in public spaces, then recorded user reactions and interactions with the device. Participants did not know they were part of a research study, until *after* they interacted with the bench. The user experience data collected from this study is valuable to understanding how to indicate affordance in publicly shared shape-changing devices.

Controlled experiments allow for robust quantitative analysis, because the testing environment and responses are consistent across participants and are repeatable. This methodology is particularly effective at validating research results and increasing our understanding of the user-experience with shape-change.

2.5 Summary

SCI research faces several major challenges, including selecting appropriate applications, creating application development tools, and understanding the user-experience. In working to solve these challenges, researchers have produced fascinating prototypes and obtained important insights using a variety of evaluation methodologies. However, very little work has been done specifically in *reconstructible* devices, necessitating new terminology and a unified research vision. This project adds a new prototype design that is both *tearable* and *connectable* for a fully reconfigurable interface. Like many other studies, we evaluate and explore ReConstructibles through design workshops. However, we go further than this by conducting two deployment studies. Deployments are rare in SCI research: of the projects we analyzed above, only two ran "in-the-wild" prototype deployments. We would like to see more deployment studies, because they offer invaluable perspectives on the user experience with shape-change.

Chapter 3

Design Workshop: New Applications

Before developing hardware prototypes, we wanted to deepen our understanding of how people experience shape-change, especially how they experience *reconstructible* devices. In particular, we looked for application domains for which ReConstructibles are ideally suited. We wanted to know how *reconstructibility* benefits users and how small to make ReConstructibles. We assumed that the ideal size would be very small, because it would maximize reconfiguration possibilities, but we needed to test that hypothesis. These insights would guide our development of working devices.

To achieve these objectives, we ran a series of design workshops. In these workshops, participants experienced ReConstructibles through low-fidelity prototypes, using model devices to generate new application ideas.

3.1 Study Overview

We recruited 17 participants (27.6 mean age, 9.13 standard deviation, 8 females, 8 computer scientists, recruited from Swansea University students and staff) which we split into 6 sessions. Each workshop session included 2-4 participants and lasted around 1.5 hours.

Workshop sessions were divided into two parts. In each part, participants designed new applications for a particular scenario or topic. The design activities were based on the dialogue-labs method [26], using the scenarios as seeds for ideation. Participants used model devices (described in Section 3.1.1) as props for designing their applications. Prior to beginning the design activities, the facilitator clearly outlined to participants the capabilities and limitations of ReConstructibles as described in Section 3.1.2.

The facilitator also asked participants to stay away from ideas closely related to gaming. There is already a large body of SCI literature addressing shape-changing gaming applications, and even several commercially available games (e.g., WOWCube[1], a Rubik's Cube-like device with touchscreens instead of colored tiles). This application domain has been extensively studied and implemented, but with mixed results. Often games don't have long-term replayability, causing users to lose interest after the novelty wears off. We felt our project was best positioned to contribute to the study of other aspects of SCI. Thus, we leave gaming application to future work and didn't take further any gaming ideas that came out of this workshop.

Part 1 used researcher-selected scenarios. We chose the scenarios described in Section 1.1, because we considered these two of the most promising application domains. Typically, in a shape-changing interface, shape-change is used to control a device or to change the device's function. Our scenarios explore both options. Scenario 1 focuses on the affordance of reconstructibility as a means of device control. It revolves around children as users to encourage study participants to design simple interactions that utilize reconstructibility. Scenario 2 focuses on the possibility of repeatedly changing the device's function, essentially creating many devices from a single device. This idea is popular in the SCI research community as a way of reducing waste from creating many single-purpose devices. We used this scenario to encourage participants to design for and evaluate this concept. These scenarios were presented to participants with a simplified explanation, leaving out our own application ideas and simply framing the scenario in terms of people and their needs. Focusing on these scenarios in our workshops allowed us to evaluate our hypotheses about key applications.

In Part 2, participants selected scenarios from a list of human activities generated by the researchers. It can be difficult to inspire new application ideas in lab-based studies. Because workshop environments are often similar to an office space, generated ideas often revolve around office situations: working at a desk, interacting with colleagues, etc. We wanted to push beyond these domains, so we drafted a list of other activities, most of which take place outside an office environment. These activities were described in generic terms, such as "Public Speaking" and "Car Repair" (see Table B.1 for the full list of possible topics). Participants pulled three topics at random from the list, then selected one of the three options to work with for Part 2. This allowed them to select a topic with which they had

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[1] https://wowcube.com

some degree of familiarity, thereby keeping the flow of the design experience unobstructed by confusion and lack of information. These scenarios were broader in scope than the researcher-selected scenarios, so participants were encouraged to narrow their topic to a few specific activities. This half of the workshop allowed us to explore new territory, searching for applications in areas participants and researchers might otherwise miss.

For each part, participants worked first in pairs to design applications. Then, taking turns, pairs shared their findings with the entire group, which "elaborates upon and evaluates" the ideas informally through group discussions [26]. At the conclusion of each discussion, all participants evaluated the ideas formally using the application evaluation forms described in Section 3.1.3. These evaluations provided a consistent measure for comparing results between application ideas within a particular session and comparing participant responses across different workshop sessions.

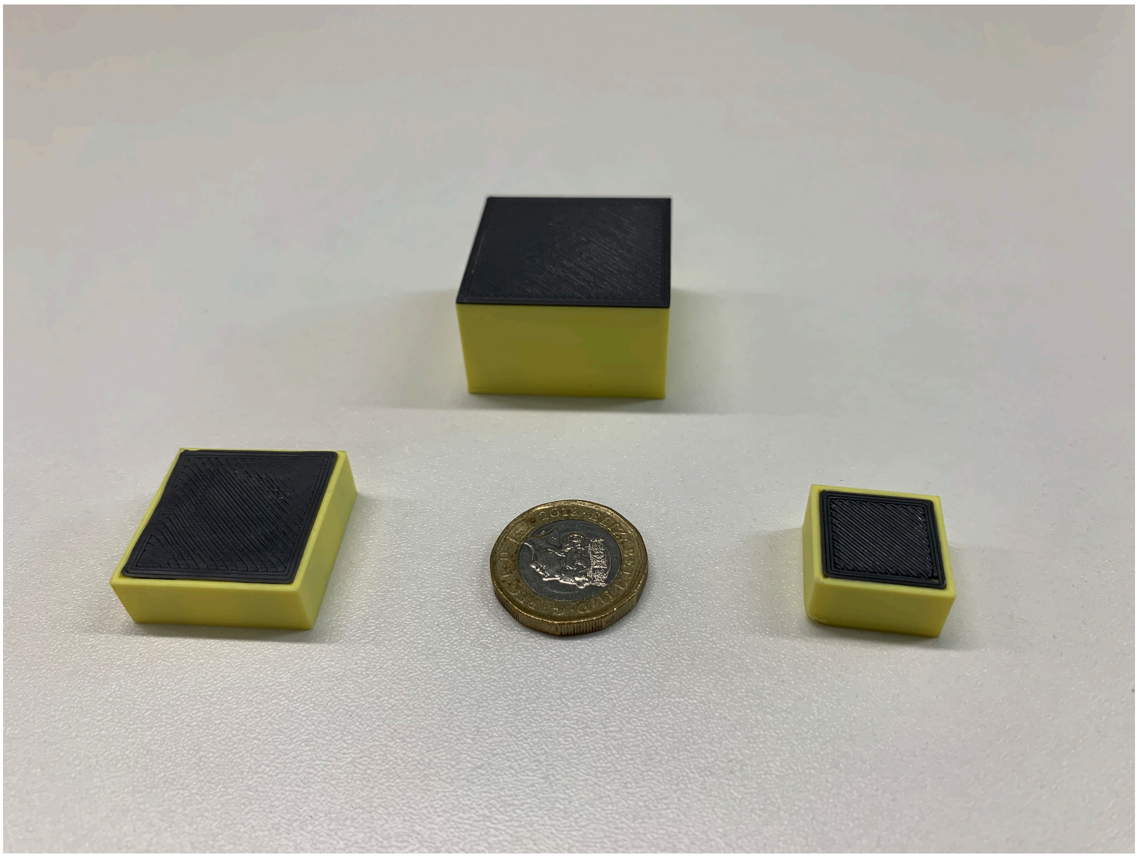

Figure 3.1: Model ReConstructible Devices. All three model sizes are shown with £1 coin for scale. From left to right: *Medium* (27mm x 27mm x 9mm), *Large* (36mm x 36mm x 20mm), and *Small* (18mm x 18mm x 9mm).

3.1.1 Model Devices

Design workshops often give participants brainstorming materials, such as Legos and sticky notes to facilitate their ideation and designs. These tools are helpful, especially in the early stages of testing a new interface concept. However, once the basic design has been established, higher-fidelity tools are needed to flesh out ideas and explore more realistic scenarios. In our project, we introduced model devices as participants' primary ideation materials.

Our model devices were 3D printed cuboids with a grey cap on one face to represent the device's touchscreen (shown in Fig. 3.1). Models had magnetic connectors and no electronic components. The user interactions of *tearing* and *reconfiguring* the model devices were identical to how users would interact with the working prototypes we later developed. Consequently, the model devices served as excellent placeholders for fully-functioning prototypes.

Using these models in our workshops gave us several key benefits. First, they enabled our participants to physically experience a *reconstructible* interface. The applications they designed felt more real to them. They could factor in device size and test out real configurations. Second, they could explore new interaction possibilities, such as sticking cubes to metallic surfaces or connecting cubes in non-traditional ways. And third, using models allowed us to examine the effect of device size on the user experience. We created three model sizes as shown in Table 3.1. We started with the *small* model size because it represented what we considered the "ideal" ReConstructible. This dimension made for a display that was barely larger than a standard computer keyboard key. A *small* ReConstructible would be able to display a piece of actionable information or controls, such as a piece of text or a button. Since more compact dimensions allow for finer control over device configurations, we assumed this would be the most useful device size. That said, early stages of prototype design and development had given us insights into the size of working prototype we could reliably build. This was the size of the *large* models, which became the second size we selected. The *medium* model size is halfway between the two other sizes. Prior to our user evaluations, we thought we knew what the "ideal" ReConstructible would look like. Using different sized models in the workshops enabled us to test our assumptions in this regard.

We selected a cuboid form factor for three reasons:

Size	Dimensions (w x h x d in mm)
Large	36 x 36 x 20
Medium	27 x 27 x 9
Small	18 x 18 x 9

Table 3.1: Model Device Dimensions

1. *Cuboids can be intuitively and arbitrarily reconfigured by users*. Users don't need to worry about aligning matching edges and can easily see where a new cuboid can connect to a larger configuration. And it is easy to imagine connected devices as a single device. Other display shapes, such as circles, wouldn't provide the same sense of continuation.

2. *Cuboids offer a comfortable, familiar affordance to users.* Most commercially available devices have a rectangular display. Users will be familiar with this form factor. Additionally, with cuboids, connected devices present a single device edge, helping the user "forget" that the device is composed of many smaller devices. Other display shapes, such as hexagons, would result in bumpy or jagged edges.

3. *Currently available displays for constructing working prototypes are primarily square or rectangular*. We intended to build functioning ReConstructibles from off-the-shelf components. Using a cuboid form factor made it easier to source useful parts for prototype development.

The decision to use cuboid-shaped models and only three sizes was difficult. Given the many possible sizes and shapes, we needed to pick a narrow subset of designs to ensure our research was cohesive and focused. We leave it to future work to explore alternative device shapes and sizes.

Researchers interested in using these models can find 3D CAD files for each model device in our GitHub repository[2].

3.1.2 ReConstructibles' Capabilities and Limitations

Before the design activities began, the facilitator clearly outlined to participants the capabilities and limitations of ReConstructibles:

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[2] https://github.com/FITLab-Swansea/reconstructibles

- Capabilities
  - Touchscreen display (e.g., visual output)
  - Gesture recognition (e.g., shakes, taps, device motion, etc.)
  - Wireless Communication (e.g., Bluetooth, WiFi, etc.)
  - Geolocation (e.g., GPS)
- Limitations
  - No audio input or output
  - No camera for visual input
  - No vibrations or haptic feedback

These capabilities and limitations were carefully selected to encourage users to explore *reconstructible* interactions in any setting. We removed audio and camera functionality so participants would focus on designing applications that take advantage of *reconstructibility*, rather than getting distracted by other features. And we kept remaining functionality intentionally broad so participants weren't restricted to certain environments or wireless technologies. For example, the Geolocation feature allows for outdoor environments and the Bluetooth feature allows ReConstructibles to talk to other devices. We didn't want participants to solely imagine ReConstructibles in indoor, WiFi-enabled office environments such as where the workshop took place.

3.1.3 Application Evaluation Forms

Participants used a standardized evaluation form to evaluate the application ideas generated during the workshop. This form included Likert scale questions for "Likelihood of Use" (how likely the participant would be to use ReConstructibles for the given application scenario) and "Comparison to Existing Solutions" (how ReConstructibles compares to existing solutions for the given domain). These scales ranged from "Very Unlikely" to "Very Likely to Use" and "Much Worse" to "Much Better than Existing Solutions" respectively. The rest of the evaluation form was open-response questions where participants listed existing solutions and recorded the reasons behind their response to the Likert scale questions. These forms provided a consistent evaluation for each application domain, making the resulting comparison of domains more robust.

3.2 Study Procedure

Workshop sessions were divided into the following segments:

3.2.1 Segment: Introduction (15 minutes)

The facilitator welcomed the participants and explained the main purpose of the workshop in a *comfortable and relaxed atmosphere* [26] enabling creativity. They were told that the goal of the study was to explore possible application scenarios and generate ideas for future applications of a new interface. A slide presentation introduced participants to the concept of shape-changing interfaces generally, pulling from relevant research work. Next, the facilitator explained the ReConstructibles concept. Participants learned that shape-changing behavior serves two purposes within the ReConstructibles system:

1. Shape-change adapts how users interact with ReConstructibles to accomplish different tasks
2. Shape-change serves as input controls to ReConstructibles

At the end of the presentation, the facilitator clearly outlined the capabilities and limitations of ReConstructibles. Then, they handed participants model ReConstructibles that would be used throughout the workshop. Half of the workshop sessions used *large* models, while the other half used *medium* models. This methodology was determined after conducting a pilot study in preparation for the Design Workshops, during which we gave participants multiple sizes at once. We expected them to use each size for different types of tasks, which would provide us valuable insights on how users perceive the variable usability of each size. Instead, pilot study participants combined multiple sizes together into a single configuration. While creative and interesting, these designs were too difficult to analyze and compare between multiple study sessions. Thus, we chose to limit each workshop session to a single size to keep participants focused and our results tractable. We also needed to start with the baseline level of ReConstructibles design, which would be a single size. We leave it to future work to explore the simultaneous use of multiple device sizes.

Participants were given a few minutes to play around with the model devices, familiarize themselves with cell-composed physical reconfiguration, and ask questions to clarify their understanding of the ReConstructibles concept.

3.2.2 Segment: First Design Activity in Pairs (10 minutes)

Participants were randomly divided into pairs. For this activity, each pair was assigned one of the two researcher-selected scenarios. Participants were asked to consider 1. What tasks they needed to perform in the given scenario and 2. How they would use ReConstructibles to accomplish those tasks.

In sessions with four participants, both scenarios were used. In sessions with two or three participants, all participants worked together as a group and only one scenario was used. Each pair also received 15 model devices and pen and paper for note-taking. They were given 10 minutes to design ReConstructibles applications for the given scenario.

3.2.3 Segment: Idea Sharing and Group Design (20 minutes)

All the participants once again gathered as a single group. Each pair led a 10-minute group design activity, building on their scenario and generating ideas. The other pair of participants gave feedback, suggested improvements, and invented new ideas. The facilitator occasionally asked questions to clarify information or to guide the conversation away from one participant dominating the discussion.

Immediately after each group design activity, participants evaluated the new applications using the evaluation form described in Section 3.1.3.

3.2.4 Segment: Second Design Activity in Pairs (10 minutes)

Participants were again randomly divided into new pairs. Each pair drew three topics at random from a bag and selected one to use for the activity. Unselected topics were returned to the bag for use in future sessions, while selected topics were removed from the pool of options. Consequently, each workshop session evaluated 1-2 unique application domains. This approach allowed us to explore a wide range of potential domains, especially ones that participants might not consider while sitting in a controlled workshop environment. To help participants focus their efforts, the facilitator suggested they pick a few specific activities within their topic, rather than trying to design applications for the topic as a whole.

Pairs received the same materials as in the first activity (15 model devices and note-taking supplies). For another 10 minutes, they designed ReConstructible applications and interactions for their chosen topic.

3.2.5 Segment: Idea Sharing and Group Design (20 minutes)

Just as before, pairs shared their topic and ideas with the whole group and led a 10-minute group design activity. These topics were also assessed using the application evaluation forms immediately after each design discussion.

3.2.6 Segment: Exit Interview and Size Comparisons (15 minutes)

To get final feedback on ReConstructibles, the facilitator conducted a semi-structured group interview with all participants. The facilitator asked participants to comment on what they enjoyed and what they found challenging about ReConstructibles. Next, participants rated the intuitiveness of ReConstructibles as an interface using a Likert scale ranging from "Very Unintuitive" to "Very Intuitive". This question was saved for the final workshop segment to give participants the maximum amount of time to get past the novelty of the interface.

At the end of the interview, the facilitator presented participants with all three model ReConstructible sizes. They were allowed to play around with *small*, *medium*, and *large* models. This was the first time participants had seen or handled two of the three sizes, since only either *large* or *medium* models were used during their design activities. Participants were asked what would change about their experience if ReConstructibles were bigger or smaller than the devices they'd been using during the workshop. Participants gave feedback on the benefits and limitations of each size.

Finally, participants were thanked for their participation and the workshop concluded.

3.3 Analysis and Results

After each group design activity, participants completed application evaluation forms as described above (Section 3.1.3). Their responses were tabulated in a spreadsheet and sorted based on whether the session used *large* or *medium* sized models. Quantitative data from the Likert Scale questions were analyzed for patterns and average responses, comparing between *large* and *medium* model sessions. Qualitative data from the open-response questions were analyzed through researcher impressions when reviewing the data. This part of the analysis was conducted more informally since the study was very exploratory and design-centered in nature. Through several passes through the data, we identified patterns of user experiences, attitudes, and behaviors. We compared between *large* and *medium* model groups.

The study facilitator also recorded their observations from the design workshop sessions and the group discussions in particular. These were analyzed in a similar fashion to the open-response evaluation questions. Facilitator notes were compared against the application evaluations. We sought to identify themes in user motivations for using and evaluating ReConstructibles.

We note that we additionally collected anonymized demographic information from participants. While we did not design our study to test differences based on demographics, we included the data in case it had introduced unexpected bias in our results. However, we saw no significant patterns that could be explained by participants' age, gender, educational background, or technological expertise.

What follows is our analysis of the results of the design workshops. In our discussion, we interleave quantitative and qualitative results to provide a clear narrative for the conclusions we draw.

3.3.1 Impact of Device Size

Before conducting this study, we assumed that the "ideal" ReConstructible device would be very small. A small device has higher *granularity*, which allows for more complex configurations. We hypothesized that more complex configurations would unlock more functionality and make ReConstructibles more useful to people. Thus, when we created model devices to test in the workshop, we expected the *small* models to be participants' favorites. Our study results suggest that this isn't the case, but that the ideal ReConstructible is somewhere between the *medium* and *large* models.

The first evidence for this is found in the configurations participants used to run the applications they designed. ReConstructibles are fully reconfigurable and capable of interesting shapes, such as crosses and right angles. Most participants loved to create complex shapes, but only when they were simply fidgeting with the models. When imagining practical applications, they drifted toward simple, practical shapes. Often participants would imagine using the devices all together in a rectangular grid or individually, breaking off single devices for single functions. They struggled to find reasons to configure ReConstructibles into intricate patterns, thus a few large cubes are easier to work with (and have fewer bezel breaks) than twice their number in small cubes. And since most participants liked to use single devices for certain tasks, cubes need to be big enough to be useful on their own. The *small* models are barely big enough to display a single button, which means they are very difficult to control on their own. A larger device has more room on the display for multiple controls and can display more textual or graphical information.

The second reason in favor of a larger ideal ReConstructible comes from the exit interview segment. During this group interview and after handling all three sizes, on average participants indicated that their preferred device size was whichever size they'd been using in the workshop. These models had become familiar and comfortable to them. If the group used *large* models, then they generally felt limited by the smaller sizes in terms of the information they could display. If the group used *medium* models, then generally the larger size felt clunky and inconvenient. Few participants preferred the *small* models, because most of them felt a single cube was too small to be useful.

This leaning toward the familiar device size, rather than a consensus on ideal dimensions, was further reflected in the output of the workshop sessions. We saw no major differences between *large* model and *medium* model groups in terms of the ideas generated or the participants' perceptions of ReConstructibles' suitability for the scenario they explored. The ratings of "Likelihood of Use" and "Comparison to Existing Solutions" were the same between *large* model and *medium* model groups. The only exception is *large* model groups were more likely than *medium* groups to use ReConstructibles for Scenario 1 (Sharing with Children). But the difference is slight.

In regards to device size, the only opinion most participants agreed on was they preferred the depth of the *medium* models. Most participants considered the depth of the *large* models to be prohibitively inconvenient, making it difficult to carry in a pocket and uncomfortable to hold multiple devices at once. Thus, while participants liked the size of the *large* model displays, they would want it in a housing that is less than half the depth.

These results caused us to reconsider what we defined as the "ideal" ReConstructible. A high degree of *granularity* appears to actually impede the successful user experience. It increases the effort of assembling new configurations and renders cubes unviable for individual use.

3.3.2 Evaluation of Researcher-Selected Scenarios

Here we present participants' application ideas for the researcher-selected scenarios generated during the first design activity. Some ideas were unique to a specific session, others were repeated across multiple sessions. We've organized participant contributions into use-case examples and streamlined their descriptions to make it easier to understand participant ideas in their proper context. The names used in these descriptions were chosen randomly and are not intended to represent the real names of study participants.

3.3.2.1 Scenario 1: Sharing with Children

Michael gives each child a 1-2 ReConstructibles. His children use them to send status messages. These are simple messages displayed to the child in the form of emojis or color codes. By tapping icons on the display and rearranging cubes into pre-determined configurations, they can tell Michael if they need to be picked up from school, if they are staying with friends, or if they are hurt. ReConstructibles also send Michael GPS pins of each child's location. Michael can send his children messages, such as timers to show the child how long they can play before coming home. The two-way communicate is simple, but effective. It accomplishes exactly what Michael needs without giving his children a smartphone.

3.3.2.2 Scenario 2: Customized Controllers

At night before bed, Katherine sets her ReConstructibles to display reminders for things she needs to do the next day, such as errands she needs to run and materials she must remember to bring to the office. She connects them magnetically to her fridge and goes to sleep. In the morning, as she is getting ready for the day, her reminder cubes ensure she prepares everything she needs. She scoops them off the fridge and into her pocket. At the office, her ReConstructibles display the tasks she needs to accomplish before the end of the day. She rearranges her tasks in order of priority, then gets to work. As she completes tasks, she moves the corresponding cube from the "incomplete" group to the "complete" group. Once connected to the "complete" group, the cube gives visual confirmation that the task is done. In the afternoon, she plays a game of Tetris on her cubes during a boring meeting. Upon returning home, she puts food in the oven and attaches three ReConstructibles to the oven, which display a progress bar counting down to when dinner is ready. She can see it from anywhere in her flat, so she always knows how long she needs to wait.

3.3.2.3 Discussion

The application evaluation forms (Section 3.1.3) included Likert Scale questions for "Likelihood of Use" and "Comparison to Existing Solutions". Average responses to these questions for all applications discussed below can be found in Tables B.2 and B.3. Both researcher-selected application domains received positive responses from participants, with average scores of "Slightly Likely to Use" and "Slightly Better than Existing Solutions". This is evidence in favor of our hypothesis that device sharing and device customization are useful application domains.

However, few of participants' ideas took full advantage of *reconstructibility*. Some applications, such as Michael's children using specific configurations or Katherine's task management system (both described above), used *reconstructibility* as the primary mode of interaction, but most did not. For Scenario 1, the majority of applications relied on a single cube for each child. For Scenario 2, participants typically kept 6 model devices in a 2x3 grid with no reconfiguration between tasks.

Consequently, while most participants found these applications domains relevant and beneficial, since few of their ideas required *reconstructibility*, it is difficult to conclude that *reconstructible* devices are uniquely suited for device sharing and device customization applications. Users' difficulty utilizing *reconstructibility* in their designs may stem from the challenge of evaluating a new interface with model devices in a workshop setting. This is one of the primary motivations we chose to next run a deployment study with low-fidelity prototypes.

3.3.3 Evaluation of Participant-Selected Topics

Participants' application ideas for their selected topics are shown in Table 3.2. While this is not a comprehensive list, it contains the main ideas in each category.

Despite the instructions they received regarding device features, sometimes participants invented applications that fell outside of ReConstructibles' capabilities, such as requiring a microphone. Likewise, participants sometimes designed gaming applications for ReConstructibles, despite our instruction to avoid that area. When these ideas came up during the discussions, we reminded them of Reconstructibles' functionality and our interest in non-gaming applications, then moved the discussion on to different ideas.

3.3.3.1 Discussion

In the application evaluation, the average participant scores for these applications were above "Neutral" for both "Likelihood of Use" and "Comparison to Existing Solutions". However, their discussion of the applications didn't always reflect the scores they gave on the evaluation form. They would score an idea positively, then talk about how niche

Domain	Application Ideas
Public Speaking	• Controlling presentation slides with forward and backward buttons on two cubes • Bulleted presentation notes on single cube • Audience submits questions and reactions using single cube
Music	• Physical audio playback controls (play/pause, volume, track skip/rewind) • Saving song to library
Socializing	• Share ReConstructibles with friends to locate one another if separated • At a restaurant, each cube represents a different course and patrons set and rearrange to create their meal order
Gambling	• Game of chance to assemble a specific colored configuration using tips that flash periodically across the center of the display
Concerts	• Display song subtitles for deaf or hard-of-hearing patrons • Venue broadcasts text messages to all patron's ReConstructibles • ReConstructibles sync to the music, displaying cool visuals in-time to rhythm and notes • Choose a bright color or image and wave overhead during a musical performance
Writing	• Organize and storyboard your outline or story arc, rearranging ideas and segments physically
Large-Scale Events	• Share ReConstructibles with friends to locate one another if separated • Game for children at the zoo arranging ReConstructibles into the shape of an animal
Visual Art	• In an art gallery, ReConstructibles act like a guide, providing info about each exhibition, updated by tapping device to special connector by the display • Physical controls for digital art (e.g., color palette, tool switching) • Creating pixel art by arranging and rearranging ReConstructibles
Car Repair	• Displays current task to each member of repair team to keep their workflow organized and running smoothly • Automatic call to emergency services if car crashes (device detects sudden cease in movement)

Table 3.2: Participant Application Ideas for Selected Topics

the application was and how unsure they were that they would actually use it. Though we were asking about them specifically ("How likely are *you* to use this?"), they may have interpreted the first question in the evaluation form as about the general public ("How likely are *people* to use this?"). If so, this could account for the discrepancy between their discussion and scores.

In any case, similar to the researcher-selected scenarios, most of the application ideas involved a single cube operating independently or a group of cubes in a large rectangular cluster. *Reconstructibility* featured slightly more prominently in their ideas than for the researcher-selected scenarios, but primarily as the means of switching between applications. It was rarely a key part of a particular application's interaction behavior. Consequently, none of their chosen topics established itself as an excellent fit for ReConstructibles. Thus, a low-fidelity deployment became increasingly critical to understand their experiences and realistic use-cases.

3.3.4 Feedback and Suggested Improvements

Throughout the study and particularly during the exit interview, participants provided feedback on the devices and requested new features.

3.3.4.1 Intuitiveness of ReConstructibles

During the exit interview, most participants rated ReConstructibles as either "Slightly" or "Very" intuitive on a Likert scale. The explanation for this score was near universal: interacting with ReConstructibles from a hardware standpoint is easy and natural. The magnetic connections and touch screens are familiar interactions and participants had no trouble handling that aspect of the interface. However, while *how* to use ReConstructibles was intuitive to participants, *why* to use ReConstructibles or *what* to use them for was not. Many participants reported that despite the design activities and discussions, they were still unsure for which applications they would realistically use ReConstructibles. Additionally, they expressed concerns about learning to use ReConstructibles applications. If they were given ReConstructibles, they thought it would be very difficult and unintuitive to learn which configurations launched which applications. This caused participants to rate the intuitiveness of ReConstructibles lower than they would if grading the interaction purely from a hardware standpoint. All participants felt the physical interaction was "Very Intuitive", but the software interaction was much less intuitive.

3.3.4.2 New Feature Requests

Nearly all participants requested audio capabilities, both for input and output. Many of the applications they wanted to build relied on either recording/transmitting sound or audio playback. They wanted audio confirmation of successful task completion or for notifications and alerts. For applications designed to replace the use of a smartphone (such as those for Scenario 1), they wanted ReConstructibles to be capable of making phone calls.

3.3.4.3 Device Design Improvements

Many participants were very worried about losing or breaking ReConstructibles. They liked how easy the magnets were to use, but felt that magnetic connection alone was insufficient to guarantee the devices wouldn't become accidentally separated and subsequently lost. Naturally, this concern increased for smaller model sizes.

Additionally, the *large* models were considered far to bulky for comfortable use. Most participants loved the thinness of the *medium* models and suggested their ideal device would be the display size of the *large* models, but the depth of the *medium* models.

3.3.4.4 Overall Impressions and Feedback

All study participants reported having a very enjoyable experience interacting with ReConstructibles. The magnetic connections made *tearing* and *connecting* devices easy and satisfying. They were excited by the possibilities ReConstructibles offered, but were also a little overwhelmed by them. Their responses are the first evidence of ReConstructibles' value and flexibility.

Chapter 4

Deployment 1: Low-Fidelity Prototypes

One of the main limitations of our design workshops was that participants couldn't evaluate their applications ideas in their proper context. We conducted the workshops in a university room, far removed from participants' real routines, activities, and relationships. This adds a degree of unreliability to participant evaluations, since they must evaluate applications based purely on what they *imagine* about using those applications in real life.

To discover applications that people would realistically use, we ran a deployment study with low-fidelity prototypes. We recruited 4 participants (25.5 mean age, 3.11 standard deviation, all female, 2 computer scientists, recruited from Swansea University students and staff) who had participated in our previous user study workshops. Since participants had already spent time working with ReConstructibles and designing applications, they were able to quickly move past the novelty of the interface as they considered ReConstructibles in real-world contexts. The deployment study lasted for 1 week, during which participants took model devices home and used them to design new applications. This also enabled us to study the ReConstructibles' user experience and gather application ideas "in the wild," rather than in a controlled workshop environment.

4.1 Study Overview

4.1.1 Model Devices

For this deployment, we needed to select a single model device size Table 3.1 for the participants to use. In our last study (Chapter 3), participants gave positive feedback about the *large* model touchscreen size. They wished the models were as thin as the *medium* size, but typically wanted the *large* display to make each individual cube more functional. Additionally, in our preliminary device development, we learned that we could build working ReConstructibles prototypes that were the same size as the *large* models. For these two reasons, we chose to use the same *large* models for the deployment as we used in the workshops. This allowed us to meet participants' needs and meant that results of this study would better inform our device development.

4.1.2 Deployment Procedure

Each participant received six *large* model ReConstructibles. We chose this number to balance configuration possibilities against participant convenience. While more devices may have enabled participants to generate more complex configurations, any more than six would have been inconvenient to carry on their person. We wanted participants to easily take the model devices with them throughout all of their weekly activities. Six devices was still sufficient for creating a wide variety of configurations, so we provided that many model devices to the participants.

Participants were instructed to carry the model devices with them for 1 week, making sure to have a few devices on their person at any given time. They were asked to go about their personal and work routines as normal, but to frequently consider the activities they were engaged in and how they might use ReConstructibles for that activity. The model devices served as props for designing and evaluating new applications.

Participants recorded their ideas in a digital diary. The digital diary was an online form where they could describe the application and upload photos or videos of specific configurations or settings. While participants could record their ideas at any time, the study facilitator sent out reminders twice a day. One reminder went out every evening at 7pm. This was so participants could review their day and record any ideas they'd forgotten to submit earlier. It was late enough that they would likely be home from work, but early enough to still be noticed before they went to sleep. The second reminder went out at a random time each day. This helped participants remember to record ideas throughout the day, not just at the end. The random reminder also served as a prompt for participants to consider whatever they were doing at the moment the reminder was received.

At the end of the deployment, the researcher met with participants two at a time to debrief on their experience and impressions. We would have preferred to meet with all four participants together, however, to do so, we would have needed to wait an entire week. We opted to meet with two participants at a time so we could hold the debriefing sessions within two days of completing the study. This kept their memories and impressions of their experiences fresh for discussion. During this meeting, researchers and participants discussed the ideas generated by all participants, as well as the themes and concerns researchers noticed from analyzing the data. Participants were given a £20 gift voucher as compensation and appreciation for their participation.

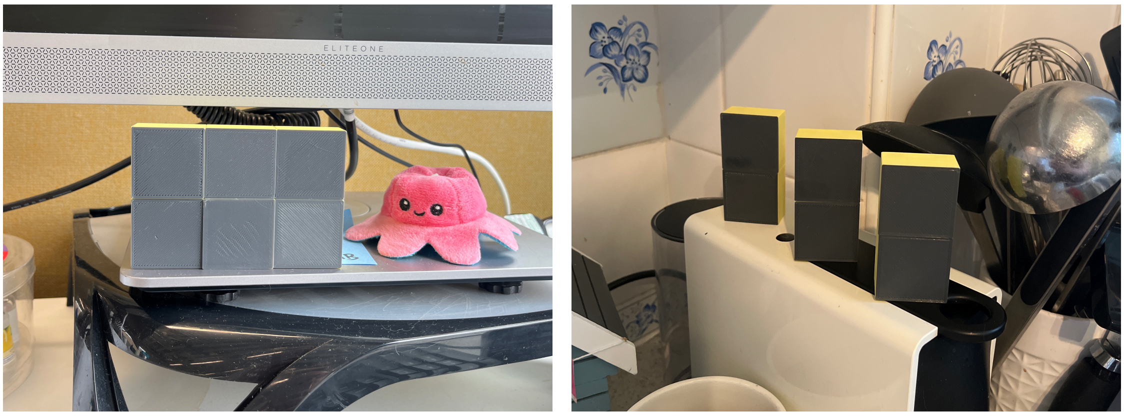
4.2 Analysis and Results

Participants submitted 53 ideas, 16 of which included photos. These ideas were tabulated in a spreadsheet for easier analysis. We grouped ideas into thematic categories. Since there wasn't a sufficient number of ideas or participants to warrant a formal thematic analysis, so we instead conducted a simplified thematic analysis. To this end, we made several passes over the data, seeking to capture the primary goal of each application idea. In the first pass, any ideas that were completely or nearly identical were put together. From these, we began to detect patterns in how participants imagined using their devices, which we used to define our categories. In subsequent passes, we refined our categories until we reached a point where we felt we had extracted the key elements of each application design. Ultimately, our analysis produced 11 thematic categories. These themes covered a wide variety of application possibilities, though several categories contained only one or two of the 53 application ideas.

The researcher also took notes during the end-of-study debriefing sessions. In these sessions, the researcher first asked about participants' experience generally during the deployment. Second, the researcher reviewed with the participants the thematic categories with the most ideas and shared some of the specific ideas participants had designed for each theme. The simplified thematic analysis was conducted ahead of the debriefing session to facilitate this conversation. During this part of the session, participants described the motivations behind their application ideas, their experiences, and their thoughts and feelings about these ideas. Third, the researcher reminded them about the researcher-selected scenarios from the workshop study and asked them to reflect on those scenarios based on their experience in the deployment. Since all participants in this study were recruited from the design workshops conducted earlier, it was important to see how their understanding of and feelings toward ReConstructibles had evolved. Finally, the researcher concluded the debriefing by leading a discussion on how participants would improve ReConstructibles.

We reviewed these notes for trends, especially experiences shared by multiple participants, and key participant motivations for using ReConstructibles. The debriefing session notes in combination with the generated ideas helped the researcher paint a clear picture of how participants imagined using ReConstructibles, why those applications were relevant to them, and how effective they felt ReConstructibles were for those applications. Our results are presented below.

4.2.1 Application Ideas



a) Ambient Desk Display

b) Timers for Cooking

Figure 4.1: Application Examples with Low-Fidelity Prototypes. Participants submitted these photos during the deployment study. (a) Jonathan sets his ReConstructibles to display images from his family trip. He places his devices on his work desk and enjoys looking at them throughout his day. (b) Jennifer uses ReConstructibles to help her cook. She breaks off several cubes and sets timers for different parts of the dish.

Here we present application ideas for the most popular and interesting themes as descriptions of example scenarios where the application would be used. These descriptions don't cover every application idea submitted, but described commonly repeated actions to demonstrate how participants imagined using ReConstructibles for each theme. Any specific idea not included these descriptions can be reasonably inferred from the examples provided. Again, the names used in these descriptions are randomly selected and do not refer to specific study participants.

4.2.1.1 Ambient or Background Display

Jonathan sets his ReConstructibles to display images from his family trip. He places his devices on his work desk and enjoys looking at them throughout his day (Fig. 4.1a).

Grace places her cubes where her colleagues can see them, but where they don't distract her. When she's busy and doesn't want to be disturbed, her ReConstructibles display a message communicating that to her coworkers. She periodically updates the message to reflect her availability to her coworkers, such as how long until she has a break, if she's happy to chat, or if she's in a meeting.

Brandon preferred to use his ReConstructibles on his nightstand to display the weather and time when he wakes up. He has the remaining cubes show interesting patterns that make for a pleasant aesthetic accent to his room.

4.2.1.2 Reminders and Timers

Jennifer uses ReConstructibles to help her cook. She breaks off several cubes and sets timers for different parts of the dish (Fig. 4.1b). This helps her prepare a delicious dinner. And if she needs to leave the room, she hands her husband a timer to keep an eye on, so the food in the oven doesn't burn.

David makes a list of everything he needs to remember to take with him to work or accomplish in the morning. He transfers the list to his ReConstructibles, then places cubes around the house in visible locations. Some are stuck to the fridge, others on his door, and others in the bathroom. As he goes about his morning routine, he collects cubes as he accomplishes everything on his list.

Ruth sets each cube to display one of the tasks she needs to complete at work. One cube displays the word 'Done' and a bright green border. When Ruth accomplishes a task, she moves the corresponding ReConstructible to the 'Done' cube and the 'task' cube, too, turns green. She stays motivated by watching her block of completed tasks growing bigger as more cubes are connected together. When all tasks are finished, the ReConstructibles update their displays to show her a pretty picture and a congratulatory message.

4.2.1.3 Messaging

Eli leaves his phone at home, but takes a ReConstructible with him when he goes for a morning jog. He sends quick messages home to his wife so he knows when he'll be back or if he's injured. His ReConstructibles are also linked to emergency services, allowing him to call for help if the situation is urgent.

Melanie and her friends use ReConstructibles to communicate at social gatherings. They help find each other in a crowded space or to pool suggestions and requests for songs, drinks, games, etc.

4.2.1.4 Sharing Information

Theo's large family often has trouble keeping everyone's schedules straight. Everyone sets up his or her calendar individually on their personal set of ReConstructibles. Then at a family planning session, they connect all the family's ReConstructibles together to assemble the family calendar. They moves cubes around to see where everyone needs to be and which events conflict with each other.

Swansea University uses ReConstructibles to track student attendance at lectures. As students enter the room, they quickly connect and disconnect one of their ReConstructibles to a university cube that has been fixed permanently to the wall. This logs which students came to their lectures.

4.2.1.5 Learning Tools

Sam is trying to learn German and uses ReConstructibles to practice. One cube displays an English sentence he needs to translate. The rest of the cubes display words and phrases in German. He swipes on different cubes to cycle through the various options. Then he assembles his best guess for the proper German translation and connects this guess to the cube displaying the English sentence. The correct cubes light up green and the incorrect blocks go red. He repeats the exercise until he gets it right.

4.2.1.6 Gaming

Erika uses ReConstructibles to enhance her role-playing campaigns. Some cubes act as dice, while others serve as game pieces, representing game bosses, player data, or interactive artifacts.

4.2.1.7 Other Ideas

We focused our attention on themes with more than two ideas to emphasize what participants were most interested in. There were several cases where only a single participant suggested an application for a particular theme. We chose not to develop these further, however, for completeness, we list them here.

- Fidget toys (e.g., users simply arrange and rearrange cubes into random configurations)
- Measuring environment dimensions
- Controllers for other devices (e.g., TV, lights, air conditioner)
- Vehicle satellite navigation
- Object tracking through GPS

4.2.2 Interaction Patterns

During our analysis of participants' ideas and in the final participant debriefing session, we discovered some interesting interaction patterns.

First, the categories with the highest concentration of generated ideas involved the display of information. 21% of ideas (11 of 53) were for ambient, non-interactive displays: background animations, images, personal information (e.g., time, weather, calendar events), and public information (e.g., availability to colleagues, museum exhibition information). 23% of ideas (12 of 53) were displays with minimal interactions: reminders, to-do lists (e.g., groceries, tasks), timers, daily countdowns (e.g., for taking out the rubbish and recycling bins), and simple readings (e.g., recipes).

A full 44% of applications fell into these two categories, with the other 56% scattered across the remaining nine categories. Not only was this the highest concentration of ideas, but participants also shared that these were the applications they would most likely use in real life. In fact, most participants cited these applications as the primary reason they would want to own ReConstructibles if they were commercially available. Other categories, such as messaging, information sharing, location-related services, smart-home controls, and gaming, were not compelling use-cases to participants. They felt existing devices (e.g., smartphones, remote controls, game controllers, etc.) were already optimized for these tasks and ReConstructibles would either be more work or just a less effective experience. With ReConstructibles, they were drawn to the possibility of extracting functionality from their smartphone to an external device. They all loved having multiple devices simultaneously providing readily accessible information and features.

The second pattern we identified was that participants preferred minimal, straightforward interactions. This was reflected in their application designs focusing on information display. But it was also demonstrated by the configurations participants used for their ideas. Just as in our design workshops, participants typically relied on one of two types of configurations: 1. All or most cubes connected into one large rectangle (2x2 or 2x2 cube grids) or 2. Individual or single-paired cubes (1x1 or 1x2 cube grids). They all explained that while they were initially excited by the *idea* of fun, complex configurations, when thinking of actual use-cases, they found themselves returning time and again to simple, familiar configurations. In many cases, they intended to leave single cubes around their home and workstation so they would always have access to specific functionality (e.g., a timer cube in the kitchen, reminder cubes always on the refrigerator, task cubes on their desk). Participants didn't plan usually on recombining devices later, stating that the benefits of having dedicated devices in specific locations were higher than constant reconfiguration.

A third interaction pattern was the participants' interest in ReConstructibles' magnetic connections. They all loved to attach them to magnetic surfaces. They placed cubes on existing surfaces, such as their refrigerator and oven, and imagined installing small magnetic plates around their home and work spaces to enable magnetic attachments in a variety of locations, such as the front door or bathroom mirror. The ability to place a device somewhere easily visible then effortlessly move it to a new location was well-liked by participants. Furthermore, they found the magnetic interactions to be a very satisfying experience—everyone wanted a "fidget mode" that would allow them to absentmindedly play with the cubes while working on a different task.

4.2.3 Discussion

We are encouraged by participants' positive reactions to ReConstructibles. After a week living with model devices, their interest in having working devices only increased. They were convinced devices would be useful to them in their daily lives and were eager to receive updates on the project's progress. Clearly ReConstructibles have a positive user experience, one that goes beyond simply having engaging workshop activities.

However, this study leads us to believe that *reconstructibility* isn't as useful a characteristic as we expected. The applications participants found most useful didn't rely on *reconstructibility*, such as when cubes were used individually or when they were arranged together on a tabletop, where magnetic connections don't matter as much. Many of these applications might be better served by having a device specifically designed for the task, such as a magnetic kitchen timer or a small office display. Other applications could be just as effective with devices like Sifteo Cubes, which aren't *reconstructible* but are *reconfigurable*. In fact, many application ideas have already been explored by researchers using Sifteo Cubes, such as physical reconfiguration for learning [2]. One participant expressed that the magnetic connectivity of ReConstructibles was useful for transportation and storage, but they rarely used cubes together in a way where they cared whether the cubes were physically attached or not.

If the best configurations are simple rectangular shapes or single-cube configurations and if participants wanted specific-purpose devices, rather than general-purpose devices, then why should they use ReConstructibles? While *reconstructibility* may not be as *generally* powerful as we anticipated, there may still be *specific* applications where ReConstructibles surpass the performance of any other device. The inclination toward simple configurations may be a limitation of using model devices in the deployment. While our low-fidelity deployment was more context-driven than our design workshops, we still required participants to stretch their imagination for devices and interactions unlike anything they currently experience. Perhaps the ability to physically reconfigure the device for new applications will prove more useful in practice than in theory. A deployment study with high-fidelity, working prototypes running a few of the most popular applications ideas is critical to drawing final conclusions about the user experience with *reconstructible* devices.

Chapter 5

ReConstructibles Hardware

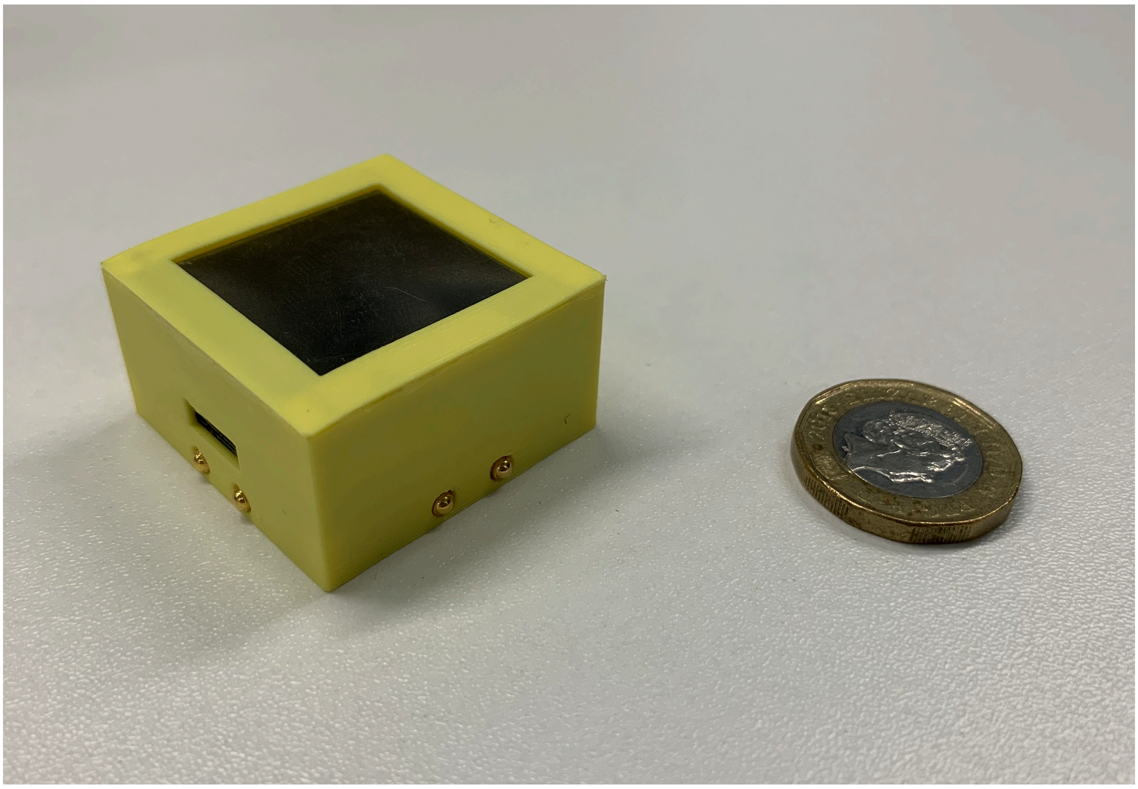


Figure 5.1: A single ReConstructible with £1 coin for scale. The device's exterior dimensions are 36mm x 36mm x 20.2mm.

We spent several months developing prototype ReConstructible devices, guided by our design workshops and low-fidelity deployment. In this chapter, we outline our design objectives and guidelines. Next, we describe and demonstrate our prototypes.

We then discuss the key decision decisions we made creating working ReConstructibles. Finally, we present our prototyping materials to the research community as a research platform for studying cell-composed devices.

5.1 Design Objectives

Our primary objective was to develop devices sufficiently robust for an "in-the-wild" deployment study. This called for a compact design, fast communication between cells, and strong magnetic connection mechanisms. ReConstructibles need to be battery-powered, so they can be used in a variety of settings. The prototypes also need a touchscreen display to enable users to control the device and to present information to the user. Finally, the device needs user-friendly setup routines and need to work right out of the box. We don't want study participants to be distracted just trying to get the device running.

A secondary objective of this project was to help people move quickly past the novelty of ReConstructibles to feeling comfortable interacting with this new interface. To achieve this, we drew inspiration from the Radical Atoms vision for human-computer interaction [60] and Mark Weiser's vision of Calm Technology [61]. Radical Atoms imagines a future where all digital information has physical manifestations that we can interact with. Calm Technology, also known as ubiquitous computing, empowers users and fades into their periphery, ultimately becoming invisible after the initial novelty wears off. Amber Case, a cyborg anthropologist, stated, "the scarce resource in the 21st century will be attention, not devices" [62]. At first, most SCIs are quite novel since they are generally very unlike devices people are accustomed to using. If interacting with an particular SCI is confusing and uncomfortable, people won't use the device, regardless of the benefits the device offers. ReConstructibles will be out of the ordinary for new users. We aimed to mitigate the inherent complexity of learning a new interface by designing interactions and behaviors that make the user's experience with ReConstructibles feel intuitive and comfortable.

5.2 Device Description

The device housing is made from 3D-printed polymer. It has a square footprint with dimensions 36mm x 36mm x 20.2mm. A square design was critical to providing maximum reconfigurability. The housing is composed primarily from three pieces—a cap

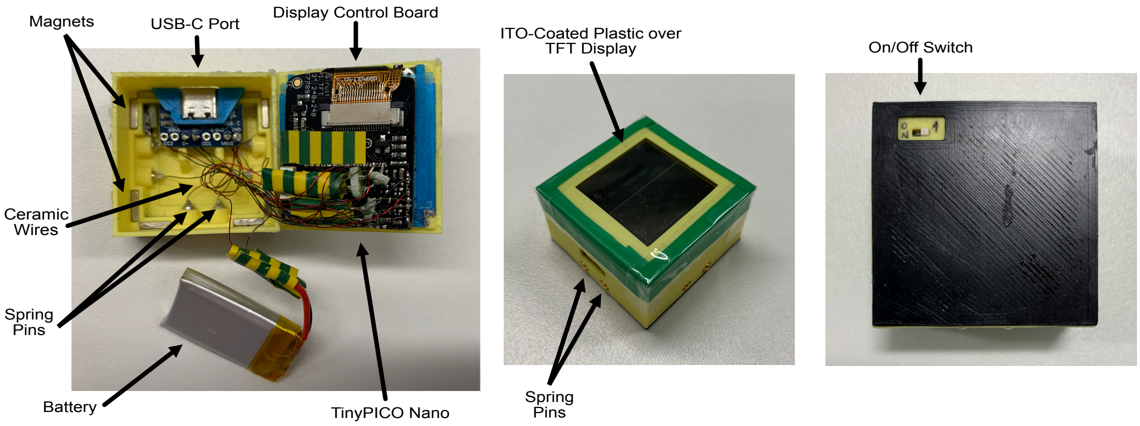


Figure 5.2: ReConstructibles hardware components. Left: View of internal components from above with casing opened to view electronic components. In assembled device, the battery fits into the housing between the USB-C port and display control board. Middle: View of assembled device from angle. ITO-coated plastic sheet is divided down the middle for left-hand (LH) and right-hand (RH) touch sensors. Right: View of assembled device from below.

and bezel, a footer, and the sidewalls—with additional support components glued to different parts inside.

Two small neodymium magnets are glued into slots just behind each horizontally-facing cuboid face. Each pair of magnets have opposite polarity, resulting in asymmetrical placement of magnetic poles. This is what allows any two device faces to connect together. The connection is strong enough to support the cube's weight, which means cubes can be reliably attached to magnetic surfaces (e.g., refrigerator, filing cabinet) and hold together in free space.

In between the magnets, two spring pins are glued into circular channels embedded in each side of the device shell. They are positioned with just the spring-loaded tip extruding from the device face. When two devices are connected, the magnets align the spring pins, forming an electrical link between the cubes. These pins transmit and receive data using the UART communication protocol.

On the bottom face of the device, the power switch is set within a small recess. This allows the device to lie flat, while still being easily turned on or off. The rest of the housing encloses a battery, USB-C port, and TinyPICO Nano[1] motherboard. The TinyPICO Nano has an ESP32 chip, which is WiFi and Bluetooth capabilities. Separated ReConstructibles use the ESP-NOW protocol to communicate with one another. The ESP-NOW protocol

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[1] https://www.tinypico.com/tinypico-nano

runs on the ESP32 chip's WiFi hardware, but doesn't require connecting to a network, meaning it works without any user configuration.

The top face of the device is composed of a 1.3" TFT display, a thin sheet of ITO-coated plastic, and the 3D-printed cap, which also forms the device's bezel. The transparent plastic sheet, glued between the display and the cap, functions as a custom-built capacitive touch sensor, which we made since the TFT display is not touch-sensitive (for more details see Section 5.3.4). The ITO-coating is divided into two channels, which listen for touch input independently. This forms two touch-sensitive buttons—left-hand (LH) and right-hand (RH). It limited our overall touch capabilities, but was sufficient for simple applications.

All components are connected together with ceramic-coated wires. These were chosen because they were thin enough to fit into the housing and able to sustain extended use.

Fig. 5.2 shows the internal and external design of ReConstructibles.

5.3 Design Decisions

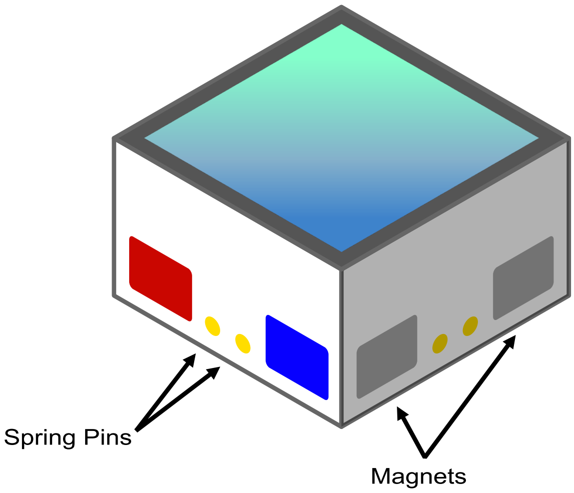

Figure 5.3: Device Connection Mechanisms. Connected ReConstructibles communicate through the spring pins via the UART protocol. Magnets placed with asymmetric polarity to ensure any two device faces can connect together. Red = magnetic north, Blue = magnetic south. Magnet placement helps align spring-pins of both devices for a strong electrical link.

In creating our prototypes, we made several decisions regarding the design of ReConstructibles' physical connectivity, inter-cell communication, cell size, and touch sensors.

5.3.1 Physical Connectivity

For a satisfying user-experience, ReConstructibles needed an intuitive and robust physical connection mechanism that clearly indicated to the user how to *tear* cells apart and how to *connect* cells together. Connected cells should also hold together firmly enough that a user can pick them up and avoid accidental separation, but not so firmly that the user can't intentionally separate them with relative ease.

In our model devices, we used magnets, because most people are already accustomed to separating and connecting magnets. We used two magnets on each face, each with different polarity. This asymmetric placement enabled any two cells to be connected together on any side (see Fig. 5.3). Participants' feedback from the workshops demonstrated that this interaction is intuitive (Section 3.3.4.1) with the model devices, so we used the same mechanism for our final prototypes.

5.3.2 Inter-Cell Communication

ReConstructibles need to be aware of how they are connected together as the specific configuration dictates the display of proper information and/or controls to the user. Cells must also coordinate the combined display, share user interactions, and exchange collected data.

Related prototypes, such as Sifteo Cubes [2] and PickCells [1], rely on a central WiFi-enabled server to coordinate communication between cells. Cells don't communicate with each other directly, rather they transmit messages to the server, which then broadcasts them to the other cells. This limits the power of these devices, because they must always be in range of the base-station.

We designed ReConstructibles to be completely self-contained, with no external server to mediate inter-cell communication (see Fig. 5.3). When physically connected, ReConstructibles communicate via the spring-pin link using the UART protocol. We chose UART because it is simple, requires only two wires, and allow any cube to transmit and receive data.

When separated, ReConstructibles communicate using the ESP-NOW protocol[2]. This is a wireless protocol built on WiFi hardware that is unique to the ESP family of microcontrollers. Since ReConstructibles' use the TinyPICO Nano board with an ESP32 chip, this protocol is available to us. We chose ESP-NOW over WiFi, because WiFi requires either configuration from the user or a dedicated WiFi network. We wanted a

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[2] https://www.espressif.com/en/products/software/esp-now/overview

communication protocol which needed no user effort to begin working and that didn't restrict study participants to a specific WiFi network. We chose ESP-NOW over Bluetooth, because Bluetooth is limited to seven connected devices while ESP-NOW can have up to 20 simultaneously connected devices.

With ESP-NOW and spring-pin communication, ReConstructibles are able to assemble the complete cell configuration on their own and can quickly transfer data between cells.

5.3.3 Cell Size

We wanted to make it easy for future researchers to replicate our work and build ReConstructibles for themselves. Consequently, we constrained ourselves to using off-the-shelf hardware components. This limited the size of our prototype to available control boards, displays, and batteries. We sourced parts from commercial vendors and designed the device around the smallest parts available to us. In some cases, we filed or sanded down development boards to fit the component into the device housing. The resulting prototypes are extremely compact with no wasted space.

5.3.4 Custom Touch Sensors

The most difficult component to source was a small, square touchscreen. Our prototypes needed to be square to facilitate arbitrary interactions and they needed to be small to allow users to hold them comfortably in their hands. However, when we found touchscreens that were the right size, they were not square, and when we found touchscreens that were the right shape, they were also too big. We determined that it was more important to fit the correct form factor of our devices than to enable complex touch interactions.

We resolved to use a 1.3" square TFT Display and develop a custom capacitive touch sensor using ITO-coated plastic, which we placed over the display. The 1.3" display component was the perfect size and shape for our devices. A custom capacitive touch sensor wouldn't allow complex touch input, but it would be sufficient for creating touch "buttons" on the display. With these sensors, we can create simple applications for ReConstructibles.

5.4 ReConstructibles Research Platform

We are very excited to have working prototype devices we can test with users. The creation of these devices mark a shift from studying theoretical possibilities to looking at real applications and user experiences with *reconstructible* devices.

We encourage researchers to replicate and expand upon our work. All of our prototype development files are stored in a GitHub repository[3]. These include detailed documentation, 3D CAD files (for both low- and high-fidelity prototypes), code listings, and assembly instructions. We make these materials freely available to facilitate future work. With the ReConstructibles hardware and software toolkit, the SCI research community can make progress toward the ReConstructibles vision and further explore *reconstructible* computing interfaces.

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[3] https://github.com/FITLab-Swansea/reconstructibles

Chapter 6

Deployment 2: High-Fidelity Prototypes

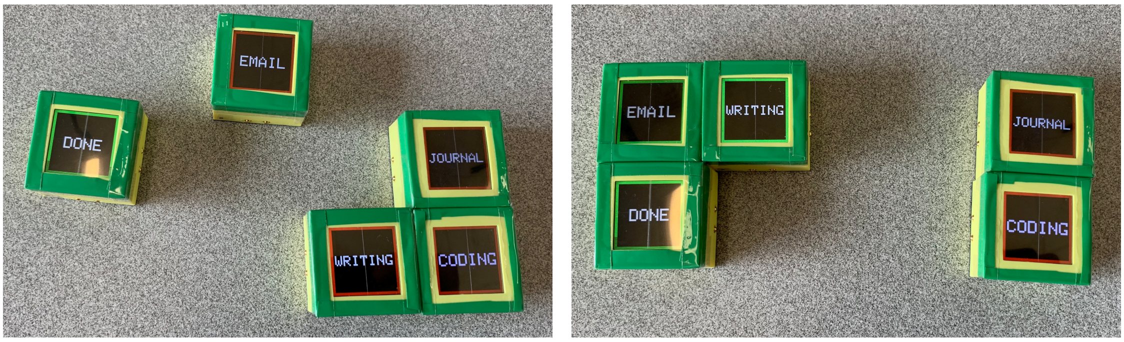
Our project culminated with a second deployment. This study used our working prototypes and three applications we designed based on ideas from the previous two studies.

We recruited 3 participants (23.33 mean age, 0.58 standard deviation, one female, 2 computer scientists, recruited from Swansea University students and staff) which we split into three individual sessions. For this study, we felt it was important to draw insights from people with a variety of previous experience with ReConstructibles. Since our applications had simple functionality, we weren't worried that they would be difficult to use for participants who were unfamiliar with ReConstructibles. Thus, we recruited one person with no prior knowledge of the ReConstructibles project or shape-changing interfaces, one person who previously participated in the design workshop (Chapter 3), and one person who previously participated in both the design workshop and the deployment with low-fidelity prototypes (Chapter 4). This selection gave us a range of prior experiences and assumptions from our participants, producing more well-rounded results.

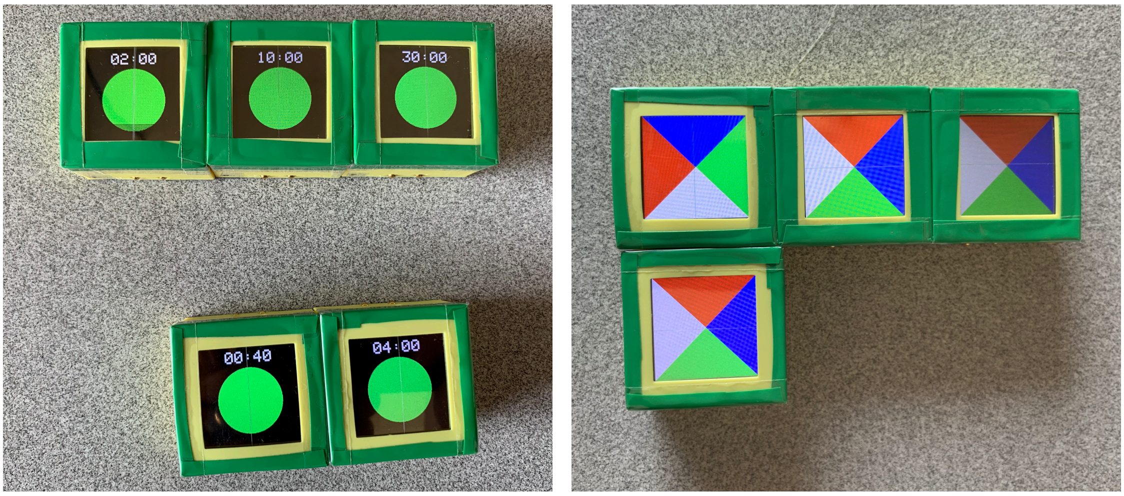
Participants received 5 working devices to use for 2-3 days to avoid overloading participants and to ensure our devices survived the full study. The devices were loaded with the three prototype applications described below. Evaluating real ReConstructibles in the real world enabled us to fully flesh out our understanding of ReConstructibles' usability.

We originally intended to give participants six devices, however we had concerns that an even number of prototypes would continue to encourage the simple configurations we saw in the previous studies. During prototype development, we made six working devices, but when one broke, we took the opportunity to test whether an odd number of devices would have an effect on participant interactions. None of the applications (described below) needed more than five devices to run properly, so our study was not hampered by the missing device.

6.1 ReConstructibles Applications



a) Task Manager App: No Tasks Completed. b) Task Manager App: Some Tasks Completed.



c) Timer App. d) Ambient Display App.

Figure 6.1: ReConstructibles software applications. (a)–(b) Task Manager: 'Task' cubes have a red border until they are connected to the 'Done' cube, whereupon the border turns green. (c) Timer: Each cube loads a unique timer value and the pie chart provides a visual representation of the remaining timer value. (d) Ambient Display: In Static Mode, each cube loads a four colored triangles which can be arranged into an interesting geometric design to display.

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We designed three basic applications based on the first two user studies: 1. Task Manager, 2. Timer, 3. Ambient Display. These apps are shown in Fig. 6.1 and described below. Full source code for these applications is in our GitHub repository[1].

- **Task Manager**

  One cube is designated as the 'Done' cube and the rest as 'Task' cubes. The 'Done' cube displays 'DONE' surrounded by a green border. Initially, 'Task' cubes display the name of the task surrounded by a red border (Fig. 6.1a). Users can cycle through available tasks by tapping on the left-hand (LH) display touch sensor. When a 'Task' cube is connected to the 'Done' cube either directly or indirectly through another 'Task' cube, the border updates to green from red (Fig. 6.1b). This provides users with tactile and visual confirmation of task completion and overall to-do list progress.

- **Timer**

  Each cube loads a unique timer value and a large green pie chart (Fig. 6.1c). The pie chart graphically represents the time remaining for when users are unable to read the numeric timer value. As the timer counts down, the pie chart changes from green to black one wedge at a time, with each wedge of the pie corresponding to 1/8th of the timer's starting value. Users start, stop, and reset the timer using the LH display touch sensor.

- **Ambient Display**

  The Ambient Display application has two modes: Static and Dynamic. When running in the Static mode, each cube loads a symmetrical geometric pattern of four colors (Fig. 6.1d). Cubes can then be arranged together to form a pattern to display. When running in the Dynamic mode, each cube cycles through 8 colors which cover the entire screen. These can also be arranged together according to the user's desires to create an animated display.

Users switch apps by tapping the right-hand (RH) display touch sensor. We note that while our prototypes can communicate using ESP-NOW and UART communication protocols, the applications we built did not necessitate the use of either protocol. We chose

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[1] https://github.com/FITLab-Swansea/reconstructibles

to keep our application simple to avoid unnecessary bugs slipping into our deployment. Our deployment focused on user experience with ReConstructibles, not on the complexity of our software applications.

6.2 Deployment Procedure

We ran three separate deployment sessions, each with one participant. For a given session, the participant was given 5 prototypes, loaded with the three applications. The facilitator explained how each application operated as well as how to take care of the devices.

Participants were instructed to carry the model devices with them for 2-3 days. They were asked to go about their personal and work routines as normal, but to look for opportunities to use ReConstructibles' applications. They didn't need to force the use of an application that wasn't beneficial to them, but engage with ReConstructibles as much as was useful and reasonable.

At the end of each day, participants completed a brief reflection in a digital diary. The diary provided a series of prompts to help with their reflection, such as "What was useful?", "What problems did you run into?", "Which apps did you use? How did you use them? Which activities did you use them for?" They were encouraged to upload photos or videos of the apps they were using and the settings where they were using them. The facilitator also asked them to provide feedback on overall device design and behavior. The facilitator emailed them each evening to remind them to submit their reflection.

At the conclusion of the deployment period, the facilitator met with each participant for a brief exit interview. During this interview, the facilitator reviewed with the participant their reflections and collected additional feedback. Participants were given a £20 gift voucher as compensation and appreciation for their participation.

6.2.1 Deployment Challenges

Unfortunately, our devices had several malfunctions over the course of the study. The biggest problems were with the touch sensors. On some devices, the left-hand (LH) touch sensor simply stopped working shortly after the study began. This meant that users could switch applications, but couldn't modify or control the current application. This primarily affected the use of the Timer App, which relies on the LH touch sensor to start and stop the timer. Naturally, participants used the Timer App far less than they would have otherwise.

Another issue was how sensitive the touch sensors could be to fluctuations in capacitance. Sometimes simply connecting devices together could cause a cube to register a touch event. This led to user frustration, especially when the device would unexpectedly switch to a different application.

Ideally, we would have liked to glue the device cap to the rest of the device housing. However, doing so would make it impossible to repair devices on the fly, should something break during a deployment session. Instead, we used electrical and clear tape to fix the device cap firmly in place. This resulted in a less aesthetically pleasing prototype and also added bulk to the outer edges, which sometimes caused spring pins to fall out of alignment. Fortunately, we never needed to open the devices for repair, since the only malfunctions we experienced couldn't be fixed without replacing the device.

These hardware and software issues should be fixed for future work, especially prior to conducting a longer-term deployment.

6.3 Analysis and Results

At the end of the study, participant responses to the digital diary reflection prompts were organized into a spreadsheet. Initially, these were sorted chronologically to give us a sense of how each participant proceeded through the study. Next, comments related to specific applications were extracted from the general feedback and grouped together. This enabled us to compare different participant's experiences with each application individually. During the exit interview, the researcher further reviewed with the participant each app specifically as well as ReConstructibles generally. We combined the exit interview notes with participant diary entries to identify patterns and interesting interactions. The researcher particularly looked for similarities and differences with how the three participants used ReConstructibles and how they described their experience. Because the study had only three participants and a short-term deployment, we had insufficient data to employ more rigorous methods of data analysis. The results of our analysis are described below.

6.3.1 App Feedback

User experience feedback on each of the three applications was overall very positive. All participants reported that they enjoyed these applications and found them genuinely useful, despite the device malfunctions and software limitations. Below we describe their feedback on each app individually.

6.3.1.1 Task Manager App

This was every participant's favorite application and the one they used the most. Participants loved the physical interaction of moving blocks from 'Incomplete' to 'Done'. They each expressed surprise at just how beneficial this application was for focusing their workflow and motivating them to stay productive. They enjoyed having this functionality outside of their smartphone, where simple actions like marking a task complete can easily lead to distraction due to notifications and other applications.

Participants reported that the magnets were a critical part of why this application worked for them. The magnetic connections made moving blocks satisfying and enjoyable. One participant liked this interaction so much that they actively sought tasks to work on so they could mark them complete. And the magnets kept the cubes neatly arranged relative to one another on the desk.

6.3.1.2 Timer App

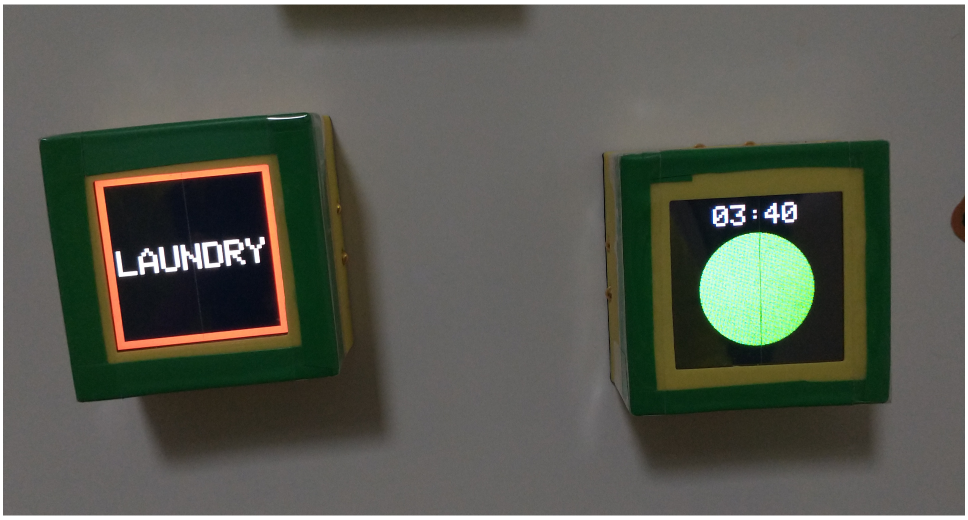

Figure 6.2: Participant submitted photo of timing their laundry. They placed the ReConstructibles on their refrigerator so they could see them from their sofa.

The most common use for the timer app was to time work tasks and activities. Participants would pair a timer with a task cube so they could track how long they had left to work. At home, participants used the timers for laundry and cooking. One participant put the timer on his refrigerator, because that was more visible than his oven and laundry machine timers (Fig. 6.2).

Use of this app was limited by the inability of users to customize the timer value. Due to device malfunctions, some device's touch sensors stopped working shortly after the study began. This rendered certain timer values inaccessible to users, since each cube had a unique timer. Even if all were working, participants wanted a way to dynamically set the timer to a value appropriate to the activity they were timing.

But malfunctions and interaction limitations aside, all participants still found the timers to be genuinely helpful to them.

6.3.1.3 Ambient Display App

This was the app least used by participants for two reasons. First, participants felt the battery life of the devices was insufficient to justify leaving the display on for purely aesthetic reasons. Second, participants didn't love the display options available to them. They wanted more attractive colors and simpler designs. They also wanted the ambient display to interact with cube placement and to synchronize with other cubes.

Ambient displays are a common application discussed in SCI literature [1, 55, 4, 54]. They were also a common application idea generated by participants in our studies. Based on this deployment, there is certainly interest in attractive, engaging ambient displays, but this alone is insufficient reason for users to want a cell-composed display. It is a nice feature to include in a prototype, but not an essential one. Future work should look at developing a simple, but effective ambient display application for ReConstructibles.

6.3.1.4 Discussion

Participants often combined apps in ways we didn't anticipate (Fig. 6.3). They connected timers to task cubes to help them focus on a specific task. One participant didn't use the 'Done' cube. Instead, he used the ambient display app in Static mode to indicate which task he was working on. He moved the ambient display cube to a new task whenever he wanted to switch his focus.

Fig. 6.4 shows additional examples of how participants used ReConstructibles. Participants' experiences with these three apps demonstrate that *reconstructibility* does have meaningful utility. *Reconstructibility* facilitated the interactions and flexibility of these

Figure 6.3: Participants combined applications together in ways we didn't expect. Here a participant used the timer to track how long they needed to work on a task and the ambient display to indicate which task they wanted to work on next. Photo taken by participant during the deployment.

applications and drew participants to the application that took advantage of it best, the Task Manager. These apps can be easily improved to better incorporate *reconstructibility* into how users interact with these applications.

6.3.2 Low Interaction Complexity

A common concern for shape-changing interfaces is the complexity the user faces in interacting with these devices. Users are comfortable working with static displays and touch controls, but physical reconfiguration is largely foreign behavior to them. One of the challenges to defining a targeted application domain for SCI is that we must prove an SCI is better than cheaper, less-complex alternatives [9].

Unexpectedly, all participants in this study reported "low complexity" as a major benefit of using ReConstructibles over their smartphones, especially to manage their tasks and timers. They felt that interacting with ReConstructibles was natural and intuitive and because ReConstructibles could only perform a few specialized tasks, the overall interaction was simpler for the user. They liked how quickly they could set up their task list or start a timer. This reaction is surprising, given the high level of concern participants had regarding software intuitiveness during the design workshop (Section 3.3.4.1). Nonetheless,

Figure 6.4: Participant-submitted photos demonstrating how they used ReConstructibles. These examples show the variety of settings and situations. They highlight how participants combined the different apps together. One of the ways participants took advantage of *reconstructibility* was to physically separate their cubes while running different applications, such as placing an ambient display in one location while using the task manager in another location.

with the addition of a few quality of life improvements, such as task customization or routine-setting and dynamic timer value adjustments, participants said they would *prefer* ReConstructibles over their smartphones for these tasks.

If these are the apps that get users to incorporate ReConstructibles into their daily lives, this might be one targeted application domain for cell-composed devices. Further work should use this as a starting point for additional application development. A longer-term deployment that takes place over weeks or months instead of 2 days would help researchers determine whether the benefits of ReConstructibles remain or wear off over time. If these prove their utility in future studies, that would be a major contribution toward the application design grand challenge for SCI research discussed in Section 2.2.1.

Chapter 7

Conclusion

In this work, we analyzed existing research in shape-changing interfaces and discovered challenges to bringing shape-change into widespread use. We learned that cell-composed devices have unique capabilities through the combination of subdivision and reconfiguration, but little recent work has explored this interface. We defined a new term for describing cell-composed SCIs: *reconstructibility*. This term emphasizes the interactive power of cell-composed devices and unifies future research with a common vocabulary. We set out to understand the benefits and drawbacks of *reconstructible* interfaces.

The ReConstructibles project offers significant contributions to three of the grand challenges to SCI research [5].

First, we present ReConstructibles as a hardware and software toolkit for research in cell-composed devices. We created high-fidelity, functioning prototypes which stand up to the rigors of "in-the-wild" deployments. The documentation of hardware and software generated by this project and made available to the SCI research community lay a foundation upon which future work can study *reconstructibility* and the ReConstructibles research vision.

Second, our user studies unearthed valuable insights into the user experience with the *reconstructible* mode of shape-change. We learned that *reconstructible* devices should not be very small, because the high degree of granularity in reconfiguring the interface requires too much effort from the user. Participants lean toward configurations that are simple and familiar, such as rectangles and squares. *Reconstructible* devices can optimize the user experience by focusing on providing functionality for these configurations.

Third, our user studies yielded promising possibilities for targeted application domains. We discovered that users were drawn to simple, straightforward interactions with ReConstructibles. The task manager application was genuinely beneficial, despite having very basic functionality and limited customization. The tangible interaction of organizing one's workflow and prioritizing necessary activities motivated participants to focus and enabled them to work more productively.

ReConstructibles is a powerful research platform for studying shape-change. This project takes several steps toward making ReConstructibles a generally available device. It serves as a launchpad for further investigations into *reconstructible* interfaces.

7.1 Future Work

We have many suggestions for future research with ReConstructibles. First, many refinements can be made to the device design that would make future prototypes more robust and capable. Second, several features could be added to the device that would foster new ideas, innovations, and insights into the user experience. Finally, this project opens up many interesting research questions and provides a platform for studying them.

7.1.1 Design Refinements

The hardware and software design of ReConstructibles could be refined in the following ways:

- **Custom PCB board**

  The vertical height of ReConstructibles could be dramatically decreased through the use of a custom-designed PCB board. Much of the height of the device was due to several layers of hardware: USB-C port, spring-pins, TinyPICO Nano, display control board. These layers could be combined into a single PCB design, with the USB-C port, spring-pins, battery connector, TinyPICO Nano, and display connector attached directly to the same motherboard. This would shrink the height of the device significantly, possibly cutting it in half. The battery could then be placed on top of the electronics, instead of trying to squeeze it next to other boards.

- **Connection Switch**

Our ReConstructibles designs used spring pins for all connected-device communication. These pins would transmit data via UART, however, UART doesn't have a built-in mechanism for device connection and disconnection events. This means the software system must continually check for a connected device. If a switch is used to communicate this information, the software doesn't need to check it, reducing software complexity and room for errors. We suggest either an electrical switch, a magnetic switch, or an IR switch. IR transceivers could also be used in place of physical spring pins. This is what the Sifteo Cubes projects uses and is an effective method of communication. We recommend considering this functionality when iterating on ReConstructibles' hardware design.

- **App Improvements**

  There are several ways to improve each application. The timer and task manager apps would both benefit from customization. Participants sometimes felt limited by the default options. The task manager could also allow users to set routines (e.g., work, home, exercise) on the 'Done' cube which would automatically update the other cubes to show tasks within that routine. The timer app could be updated to use *reconstructibility* for controlling the timer. When a timer cube disconnects from another cube, the timer could pause until the cube reconnects. The ambient display app is the least important, but requires the most work to be useful to people. It needs more aesthetic static and animated options. There could also be ways for the user to control the display, either by cycling through colors and designs or by drawing them on with their finger.

7.1.2 New Feature Ideas

ReConstructibles could be enhanced with new features and capabilities.

- **Audio Input and Output**

  The most requested feature from all of our user studies was for audio capabilities. Participants especially wanted a speaker so ReConstructibles could notify them when a timer completed or a message arrived. Future work could explore the benefits and drawbacks of adding a microphone and speaker to ReConstructibles.

- **Vertical Stacking**

Enabling ReConstructibles to stack vertically would increase the configuration possibility space, facilitating new interactions and interesting experiences. This would also make it easier to transport and store ReConstructibles. During the workshop studies (Section 3.3), participants would sometimes connect ReConstructibles bottom faces together. The resulting configuration had screens angled in opposite directions, but it made for easier transportation. Vertical stacking also allows users to build 3D shapes and devices with different affordances.

- **Unique Cubes**

  There may be certain functionality that users would find helpful in specific scenarios, but not generally. Rather than include these features in the existing hardware and thereby over-complicating the device, special-purpose ReConstructible cubes could be developed. These cubes would have a specific and limited range of functionality, such as certain sensors or signal processing capabilities. Or maybe the unique cube would be a different size, such as a larger ReConstructible acting as the "brain" for several smaller ReConstructibles. These would be connected as needed and would add functionality and flexibility to the system as a whole.

  Perhaps a special magnet type system (with specifically arranged magnetic polarities) could enforce connections between only compatible components (e.g., a sensor component with a signal processing component).

  In some cases, these unique cubes might not be cubes, but different shapes that fit their function. For example, you might have a thinner battery cube to increase power to the system (assuming devices can share power). Or a case cube that locks around several cubes holding them securely in a particular configuration.

  We did not pursue this direction, because these are part of platform evolution and are not critical for proving the foundational characteristics of ReConstructibles. We felt it better to have homogeneous devices that are true to the ReConstructibles vision, rather than cluttering the user experience with several single-purpose cubes. We leave this for future work to explore these possibilities.

- **Screens on Each Face**

Other work, such as WOWCube[1] (a Rubik's Cube-like device with touchscreens instead of colored tiles) and Cubimorph [41] has looked at devices with touchscreens on multiple device faces. Future work could examine the benefits of adding touch screens to each face of ReConstructibles cubes. Perhaps arbitrarily arranging cubes, including on any face would increase interactions. But they could also overwhelm the user or lead to unintentional interactions and behaviors.

7.1.3 Future Research Questions

In addition to making several research contributions, this ReConstructibles project paves the way for exploring many exciting research questions. Answering these questions will improve the design of ReConstructibles and its potential for commercialization, moving it from the realm of purely research applications and into real-world users' hands. Further, research in this area will have significant ramifications on advancing the field of shape-changing interfaces.

Below we list some of the key research questions raised by this work.

- **Is *reconstructibility* a desirable characteristic?**

  The results of our first two user studies, the design workshops and low-fidelity deployment, suggested that *reconstructibility* is not as valuable a characteristic as we expect. Only the high-fidelity deployment study, where users used working devices and functional apps, produced meaningful evidence in favor of *reconstructibility*. This suggests that more research is needed to validate the desirability of *reconstructible* interfaces and to define application domains where *reconstructibility* is best suited. A limitation of all SCI research is overcoming interface novelty for study participants. This is challenging in only a few short workshop sessions or deployments with model devices, where the participants are asked to stretch their imagination beyond the capabilities of any other device they regularly encounter. Could longer-term deployments embed an understanding of the utility of *reconstructibility* and therefore yield more useful applications and more positive participant feedback? Also, what should be done about the problems of a modular device, such as when a component breaks or gets lost? Future work should explore the question of desirability through

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[1] https://wowcube.com

testing more robust software and hardware, conducting long-term deployments, and evaluating methods for managing the problems inherent to *reconstructible* devices.

- **What is the best form factor for *reconstructible* devices?**

  Our models and prototype devices used a cuboid shape to facilitate comfortable, intuitive interactions for the user and affordable development with off-the-shelf components for the researchers. Further, we only examined three possible sizes. There are many open research questions regarding the appropriate form factor for *reconstructibility*. Does the cuboid form influence participants toward simple configurations? Do other shapes lead to more useful applications and configurations? How do non-rectangular shapes improve or inhibit *reconstructibility*? Future work should examine device size and shape more closely, including the simultaneous combination of different sized devices.

- **Are *reconstructible* devices replacements or augmentations for existing devices?**

  In general, participants in our three studies liked the idea of extracting certain functionality from their smartphones and tablets to a smaller, external device. They reported enjoying the simple interactions required to activate functionality they commonly use their phones for, such as timers and task management. A common attitude among SCI researchers is that certain shape-changing devices will eventually replace existing devices. Rather than thinking of ReConstructibles as replacing someone's smartphone by performing all the same tasks, future research should explore which smartphone applications can be transferred effectively to ReConstructibles for a better user experience. Researchers should also investigate the best applications for *reconstructible* devices. This includes giving special consideration to non-traditional communities, such as evaluating the fidgeting application for ADHD or autistic users.

- **How does time affect users' understanding of *reconstructibility*?**

  Our deployment study was the first of its kind in SCI research, but it is insufficient for drawing strong, well-validated conclusions about the user experience with *reconstructibility*. Our prototypes were sufficiently robust for a short-term "in-the-wild" deployment, but we faced challenges with running a longer-term study. Future work should conduct longer term deployment studies and explore the effect of time on users' perceptions of and experiences with *reconstructibility*. Do the benefits of *reconstructibility* fade after a few days when the novelty wears off or do they persist? How fatiguing are *reconstructible* interactions in the long-term? What applications do users design after spending a weeks or months with working ReConstructibles? The ReConstructibles project provides a research platform especially geared toward these sorts of studies. We need more real-world data on user experiences with shape-change if we are to find killer applications and commercializable designs. This project proves that even our limited prototypes can be programmed for useful applications and can survive an "in-the-wild" study. SCI researchers interested in exploring *reconstructibility* should refine our hardware and software designs and run longer-term studies with ReConstructibles.

- **How can we improve the design and prototyping of *reconstructible* interactions?**

  One of the grand challenges of SCI research is creating tools for application content design. The ReConstructibles is accessible to all developers and researchers as an open-source platform. It also provides lists of hardware components that can be purchased "off-the-shelf" by anyone interested in building their own ReConstructibles. This provides the SCI community with a unique opportunity for researching the design of tools for creating shape-changing application content. New designs can be easily tested on working hardware which is able to handle the rigors of unsupervised participant interactions in deployment studies. Future work should use the ReConstructibles platform to design, develop, and evaluate interactions, toolkits, and prototypes. This work will further improve the ReConstructibles platform, benefiting further research and enabling commercial developers to bring ReConstructibles out of the research lab and into the hands of real-world users.

Each of these questions will improve the ReConstructibles project, advancing this area of SCI in incredible ways. But these questions also relate to long-standing challenges in the broader SCI community with how we run studies, develop prototypes, and gain insights into the user experience with shape-change. We hope future work will take inspiration from ReConstructibles and use this platform to move SCI research forward.

7.2 Concluding Remarks

The ReConstructibles research vision opens up a world of possibilities. Our design workshops and low-fidelity deployment present a large quantity of application ideas, and our high-fidelity deployment shows that even simple applications prove genuinely beneficial. Deployments are rare in SCI research, especially with working devices that users can take home and handle without researcher oversight. This project demonstrates the immense value these studies provide. We encourage SCI researchers to conduct more deployments, using ReConstructibles as a research platform. Our hardware and software designs can be improved, but the basic functionality is present and freely available. Anyone can build and test ReConstructibles for themselves. We've outlined several possible directions for further development and research, but there are many more unexplored opportunities! We look forward to the future of SCI research in *reconstructible* interfaces.

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Appendix A

Relevant Prototypes

Research in new interaction technologies has produced a large quantity of novel prototypes. Below we list and describe those we found most relevant, inspiring, or instructive.

A.1 Shape-Changing Prototypes

A.1.1 Physically Reconfigurable Prototypes

- **PickCells:** Fully reconfigurable interface composed of square cells that operate both individually and together as a larger device. [1]

- **Blinky Blocks:** Programmable blocks that can be stacked or magnetically connected to form 3D structures. [4]

- **Robot Pebbles:** Extremely small cubes capable of creating complex 2D configurations through self-disassembly. [3]

- **Topobo:** A 3D constructive assembly device with kinetic memory, primarily used for educating children. [50]

- **Morphology Extension Kit:** Small robotic arm attached to a wrist band. The individual components of the arm are fully modular, enabling the user to modify the length and function of the robot arm. [48]

- **Mechanical Shells:** Group of physical add-ons that augment, extend, and reconfigure self-actuated tangible user interfaces. [49]

- **Sifteo Cubes:** Cube-shaped devices with a touch screen display and gesture recognition. Do not physically connect together. [2]
- **Paddle:** Highly deformable mobile device that transforms into various special-purpose controls. This gives a physical interaction to common digital operations. [51]
- **Doppio:** Reconfigurable smartwatch with two display faces. Intended to combine Paddle [51] and Siftables [27]. Avoids the complications that arise from engaging with content on a small screen with large fingers. [52]
- **Projectagami:** Foldable mobile device leveraging 2D origami forms to rapidly customize device shape and affordances. Suggested applications include navigation, web browsing, ebooks, shopping, and gaming. [53]
- **Morphees:** Flexible mobile device that is self-actuated, similar to Paddle [51] and Projectagami [53]. Modifies its shape based on the context of the currently running application. [6]
- **Cubimorph**: Modular device composed of cubes with touchscreens on each face. Cubes are attached to each other using a hinge-mounted turntable mechanism that allows for complex configurations. This concept is most similar to PickCells [1], but differs in that Cubimorph's segments cannot be separated into individually operating devices. [41]

A.1.2 Other Shape-Changing Prototypes

- **SpeakCup:** Device with two functions: audio recording and playback. Shape-change is used to signal desired operation. To record, the device is pushed into a concave shape. To play, the device is pushed into a convex shape. [15]
- **Smart Hard Hat:** Protects the hearing of construction workers by responding to dangerously loud noises by placing earmuffs over the user's ears. [17]
- **DynaKnob:** Prototype of how the creative use of shape-change can produce a dynamic button interface. [22]
- **Shape-Changing Appliances:** Three possible applications of shape-change for home appliances. [18]

- **coMotion:** Shape-changing public bench. [16]
- **Ripple Thermostat:** Used to understand how force feedback and shape-change affect the emotional experience of interacting with an intelligent thermostat. [19]
- **PolySurface:** Actuated pin-array beneath a semi-solid surface created from laser cut meshes on spandex material to enable elevation of polygonal areas. Designed for rapid prototyping of shape-changing displays. [56]
- **ShapeCanvas:** Actuated pin-array with LEDs and sensors attached to the top of each pin. Users can generate physical animations by adjusting the height and color of pins. [54]
- **ShapeBots:** Small, shape-changing swarm robots. They can individually and collectively change their shape for a variety of functions, such as for data visualization or object actuation. [58]
- **Tilt Displays:** Display comprised of a collection of individual displays that can be individually tilted and moved vertically. This can be used for collaboration, terrain modeling, presentation of 3D information, and tangible gaming. [55]
- **TiltStacks:** Shape-changing display surface that enables more complex pixel adjustments than standard height and angle actuation. In this case, TiltStacks allows for non-horizontal orientations, pixel overlaps, and variable gaps between pixels. [57]

A.2 Wearable Prototypes

- **TAILOR:** Detects injuries by using flex sensors to measure posture and arm usage. Could be adapted to change shape (perhaps by stiffening) to prevent or heal from injuries. [59]

Appendix B

Tables and Figures

B.1 Design Workshop Tables

Table B.1 shows the full list of possible topics participants could select during the second round of design activities. Participants drew three topics at random from a bag then selected one for the activity. Unselected topics were returned to the bag and selected topics were removed from the available options.

Shopping
Public Speaking
Going out with Friends
Concerts
Visual Art
Fairs, Festivals, and Carnivals
Reading
Gym
Team Sport
Foreign Language Communication
Programming
Medical
Religious Activity
Business Meetings
Therapy/Counseling
Baking/Cooking

Cleaning
Music
Gambling
Writing
Car Repair
Gardening
Cycling
Public Transport (air, bus, rail, etc.)
Animal Care
Construction
Eating Out
Child Care
Horse Riding
Driving a Car
Hiking/Walking

Table B.1: Participant Selection Topics: Full list of possible topics participants could have selected during the second round of design activities during the Design Workshops.

Application Domain	Very Unlikely	Slightly Unlikely	Neutral	Slightly Likely	Very Likely
Sharing with Children				X	
Customized Controllers				X	
Public Speaking					X
Music					X
Socializing			X		
Gambling					X
Concerts			X		
Writing					X
Large-Scale Events					X
Visual Art				X	
Car Repair			X		

Table B.2: Application Domain Evaluations - Likelihood of Use: Average Participant Response

Application Domain	Much Worse	Slightly Worse	Neutral	Slightly Better	Much Better
Sharing with Children				X	
Customized Controllers				X	
Public Speaking				X	
Music				X	
Socializing			X		
Gambling				X	
Concerts				X	
Writing			X		
Large-Scale Events					X
Visual Art				X	
Car Repair				X	

Table B.3: Application Domain Evaluations - Comparison to Existing Solutions: Average Participant Response

B.1.1 Design Workshop Results

Table B.2 shows the average participant response to the question "How likely would you be to use ReConstructibles for this application?"

Table B.3 shows the average participant response to the question "How does ReConstructibles compare to those existing solutions for this application?"