Backyard-Degradable Interactive Electronics

Katherine Song

Electrical Engineering and Computer Sciences
University of California, Berkeley

Technical Report No. UCB/EECS-2024-145
http://www2.eecs.berkeley.edu/Pubs/TechRpts/2024/EECS-2024-145.html

July 2, 2024

Backyard-Degradable Interactive Electronics

by

Katherine Wei Song

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Computer Science

and the Designated Emphasis

in

New Media

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Eric Paulos, Chair
Professor Björn Hartmann
Professor Kimiko Ryokai

Summer 2024

Backyard-Degradable Interactive Electronics

Abstract

Backyard-Degradable Interactive Electronics

by

Katherine Wei Song

Doctor of Philosophy in Computer Science

and the Designated Emphasis in

New Media

University of California, Berkeley

Professor Eric Paulos, Chair

As the demand for material goods increases, waste is accumulating on our planet at an alarming rate. Electronics in particular present significant sustainability challenges due to the energy-intensive processes involved in their production and their dependence on nonrenewable resources. Unwanted and broken devices often end up in landfills, where they do not decompose. There has been much progress across disciplines in inventing electronics with biodegradable and compostable parts, but still, sustainability and functionality are largely at odds with one another, and systems to date still rely on standard electronic components that pose recycling and disposal challenges at end of life. Additionally, the pursuit of new sustainable technologies remains a specialized domain out of reach for the non-expert "everyday maker." This not only sidelines the needs and aspirations of already-marginalized communities but also overlooks potential avenues for the development of novel systems. My research, which operates at the intersection of interactive computing, engineering, materials science, and design, envisions the creation of "backyard-degradable interactive electronics": a class of future sustainable electronics whose entire lifecycle — from initial material sourcing to the eventual return to the earth — is a creative process that invites mass participation at every stage. This thesis offers three main contributions. I detail two strategies for making such backyard-degradable interactive electronics: (1) **a materials-centric approach** for creating backyard-degradable electronic components that can come together to form standalone backyard-degradable electronics, and (2) **a systems-level approach** whereby a backyard-degradable module can be wirelessly activated and powered by conventional non-degradable energy transmitters that are already ubiquitous. Through the presentation of example systems made with these approaches, I show that backyard-degradability applied as a constraint is a *constructive* practice, opening up doors for new aesthetics and interac-

tions in new domains. (3) Finally, I present material considerations, fabrication strategies, and a generalizable framework for designing for **unmaking**, an overlooked but important extension to making that is uplifted by the practice of designing with backyard-degradable materials.

Contents

List of Figures

List of Tables

Acknowledgments

This degree is the culmination of a journey that started in 2009, when I first stepped foot into a research lab at Princeton. I would not be where I am today without the foundational guidance and inspiration of my research mentors there, Professors Sigurd Wagner and Naveen Verma. I will forever be indebted to them for their belief in me, their professional and personal mentorship, and their demonstrations of the highest standards of scientific research and academic conduct. I also must extend my belated thanks to Vladimir Bulović and Hugh Herr, my advisors at MIT and MIT Media Lab, who supported me as a PhD student when I was in their groups and also when I decided to leave and explore the world outside of academia; I am grateful for the all the learnings I have from those years and only now, looking back, appreciate how much work went on behind the scenes.

Of course, I have several people here at UC Berkeley to thank as well. I am very grateful to the present and past members of the Hybrid Ecologies Lab and Berkeley Institute of Design, who have provided invaluable feedback, advice, and empathy over the last 5 years. In addition, my PhD advisor, Eric Paulos, enabled my presence here and took a chance on me despite my lack of background in human-computer interaction. Because of him I had the freedom to explore, get lost, and eventually find my own voice. The other members of my qualifying exam committee – Björn Hartmann, Kimiko Ryokai, and Ron Wakkary (Simon Fraser) – generously took the time to give me feedback on my research and advise me on faculty applications in my last year. Outside of Berkeley, I have also been fortunate enough to find friendship and mentorship from colleagues in the design and HCI communities, most notably my co-editors of the TOCHI Special Issue on Unmaking – Ron Wakkary, Åsa Stahl, Kristina Lindstrom, Steve Jackson, and Samar Sabie – and colleagues at Accenture Labs, including Eric Gallo, Jung Wook Park, Taylor Tabb, Aditi Maheshwari, and Andreea Danielscu.

My existence as a graduate student and my research in the last 5 years were made financially possible by several fellowships and grants, including the National Defense Graduate Research Fellowship, the Berkeley Fellowship, the William S. Floyd Jr. Fellowship BearGradS Award, the Jacobs Institute Innovation Catalyst Grant program, and Accenture Labs. I would not have been able to complete this work without contributions from each and every one of these.

And finally, I am indebted perhaps most of all to the family and friends not named here who supported me at various times during this non-linear and at times strange journey. I thank you with more heart than I could ever describe here.

Chapter 1

Introduction

For thousands of years, human existence has been intertwined with materialism and the value that physical "things" bring to our lives [31]. Since the Industrial Revolution of the 18th and 19th centuries, which saw a dramatic leap in manufacturing capabilities, the mass production and dissemination of new goods and technologies has transformed socioeconomic and cultural landscapes around the world, a process that continues to this day. More recently, the invention of computers in the 1950s, followed by the invention of the Internet in the 1960s, ushered in the modern era of electronics development that we are still entrenched in today. The global "Internet of Things" (IoT) market, encompassing physical electronic devices ubiquitous throughout society today – on the body, in the home, and in the car, among other places – that are connected and controlled through wireless networks, was valued as a $330 billion USD market in 2021 and is projected to grow to $650 billion by 2026 [215]. This translates to an estimated 22.4 billion connected devices in 2026 [126].

Unsurprisingly, this rapid growth in the development of novel physical technologies and electronics hardware is also evident in research across disciplines. Within the Human-Computer Interaction (HCI) community, which has roots in user interface and software development, physical prototyping has become increasingly prevalent in recent years. In 2015, only 37 papers, or 7.6% of the total, in the Association for Computing Machinery (ACM) Conference on Human Factors in Computing Systems (CHI) proceedings included physical prototypes; in 2019, this number had risen to 145, or over 20% of all proceedings [338]. The latest 2024 CHI conference featured multiple paper sessions centered around fabrication, smart textiles, haptics, and other themes encompassing the presentation of novel materials and methods to create physical technologies.

The generation of new hardware and material things has transformed life on Earth, digitally connecting people across large physical distances, providing novel ways of collecting and displaying data, and revolutionizing medicine, among countless others. Unfortunately, while it has certainly played an important role in human health and well being, it has also contributed to a growing climate crisis. Despite the development of more advanced recycling and composting technologies, the total generation of solid waste grows year after year, with over 300 million tons being generated in the United States alone every day – almost 5 pounds per person per day [4]. Designers and design researchers in the HCI community have become increasingly conscious of the environmental impact of the materials and processes involved in their physical prototyping. Nonetheless, a 2020 review of the environmental impact of physical prototyping reported that over one-third of the nearly 500 physical prototyping papers published in the last 5 years of CHI proceedings was still done with plastics, which largely end up in the landfill, where they take hundreds of years to degrade [338].

Sustainability often remains a secondary consideration brought about late in a design process, and an unspoken assumption is that a sustainable material must approximate the material properties of its conventional counterpart to be a competitive choice. As a result, many of the materials labeled as "bio-based," "biodegradable," and "compostable" that are available on the market today have been heavily processed from their natural constituents and specifically developed to match the durability and other material properties of conventional, non-sustainable materials. Several commercially available prototyping materials, such as polylactic acid (PLA), the most popular filament for 3D printing and one featured in 25% of physical prototyping papers at CHI, are marketed as "eco-friendly," yet many such materials developed for reusable goods are so durable that they are not in fact easily broken down at the end of their life. In practice, the conditions for degradation are often very particular and unavailable in most locales, and as such, items made with these supposedly eco-friendly materials still become landfill in most cases.

The problem of resorting to materials that cannot degrade under ambient "backyard" conditions, or even materials not industrially biodegradable altogether, is especially exacerbated in the design of interfaces with electronic components. To date, biodegradable electronics — both those that are backyard-degradable and those that are industrially biodegradable — cannot compete performance-wise with their conventional counterparts. As a result, a second issue emerges: although designers are progressively experimenting with eco-friendly materials, "smart" and responsive systems still largely rely on embedding discrete, non-renewable electronics parts, such as integrated circuits and passive electronic components. Such electronics are generally undesirable from a sustainability point of view because they contain highly toxic components and require hazardous chemicals and gases to process. Unfortunately, because currently available dissolvable or biodegradable materials do not usually meet the original electronic performance specs, they cannot simply be swapped into an existing electronics design. Furthermore, while materials scientist and engineering researchers have made great strides in improving the performance of degradable electronics, such devices are often made with highly specialized equipment and materials and are too fragile to operate outside of a controlled laboratory environment. Consequently, most demonstrations to date of "sustainable" electronics that have been deployed to people outside of a laboratory environment have focused on the components surrounding the electronics, such as the housing, rather than the electronics themselves.

One might ask why we might want interactive systems that can degrade in a backyard at all? While maximizing durability may be a suitable and sustainable approach for certain electronics, like laptops and phones, there exist numerous other devices that are temporary and potentially low power in nature, such as seasonal wildfire sensors, fashion accessories, smart packaging, and on- or in-body electronics. Some such devices are used only once – sometimes only for a few minutes – due to safety risks (e.g. sensors in a remote or physically dangerous location), hygiene concerns (e.g. electrodes on the body), or cultural reasons (e.g. taboos against re-wearing the same outfit to special events). In some cases, the ideal long term solution is to change human behavior and perception – for example, in the case of combatting fast fashion. Regardless, technologies that seamlessly degrade into the environment to match the timescales for which they are actually used could be an important effort in countering our rapid accumulation of electronic waste.

In many ways, the lack of interactive systems that utilize easily degradable materials is a technological and materials problem, but there are social considerations as well. In recent years, the "maker" community has greatly benefitted from commercially available hardware development boards and software Integrated Development Environments (IDEs) that do not require a high degree of electronics or programming experience to create electronic interactive objects. Perhaps the most well known of these platforms is Arduino[1], a class of over 100 hardware products that can easily interface with one another and be programmed using a high-level programming language, such as Python. Arduino has reported an active community of over 30 million users. With such low cost and open source hardware, non-expert electronicists have developed a wealth of Do-It-Yourself (DIY) creative prototypes, many of which have become commercialized or have garnered the interest of for-profit companies [18].

However, when it comes to options for creating sustainable electronics, makers are much more limited in their toolkits. Individual components, such as solar cells and piezo generators, are commercially available, but appropriately using these is not always straightforward process. For example, Arduino boards and other similar development boards are often not power optimized, and interfacing them with energy harvesters requires an understanding of electrical power specifications, the ability to read detailed data sheets, the development of custom circuits to control voltage and current input to the board, and more skills that many non-expert electronicists do not have [258]. Furthermore, in under-resourced areas, off-the-shelf energy harvesters and other components to support self-sustaining or sustainable electronics development may not be available at all. As a result, the development of sustainable hardware is at present effectively on a non-democratic endeavour that excludes large communities of makers who have limited experience with or simply do not have access to such electronic components. In addition to being an issue of technological democracy, this situation is a missed opportunity to uncover a countless number of future designs and applications that broader populations of makers could explore and help develop. Working towards a vision of sustainable electronics that invite mass participation and development, this dissertation aims to provide inclusive and accessible technologies that leverage the creative, active, and growing communities of makers.

[1] https://www.arduino.cc/

1.1 Contribution Summary

If we prioritize the decomposability of materials in our design and DIY-friendly fabrication workflows, can we design interfaces that are durable and have enhanced functionality without sacrificing the convenience of responsible disposability? What applications and opportunities does this way of designing surface? How do we grapple with the constantly "unmaking" (decomposing, decaying, or degrading) nature of backyard-degradable materials? These are questions that are core to the work I present in this thesis. This dissertation contributes the concept and foundational realization of "backyard-degradable interactive electronics" – that is, systems that are interactive and computationally controllable but, at the same time, readily degradable under "backyard," non-industrial conditions once they are no longer needed – to the field of the design of tangible interactive systems. This work demonstrates that when we more fundamentally rethink the design of physical interactive systems, we can create interactive systems made entirely out of biodegradable — even backyard-degradable — materials. Backyard-degradable systems seek to balance a high degree of electronic interactivity, best exemplified by prior and current efforts in materials science and engineering, with a low degree of fabrication complexity, best exemplified and valued in the design and HCI communities.

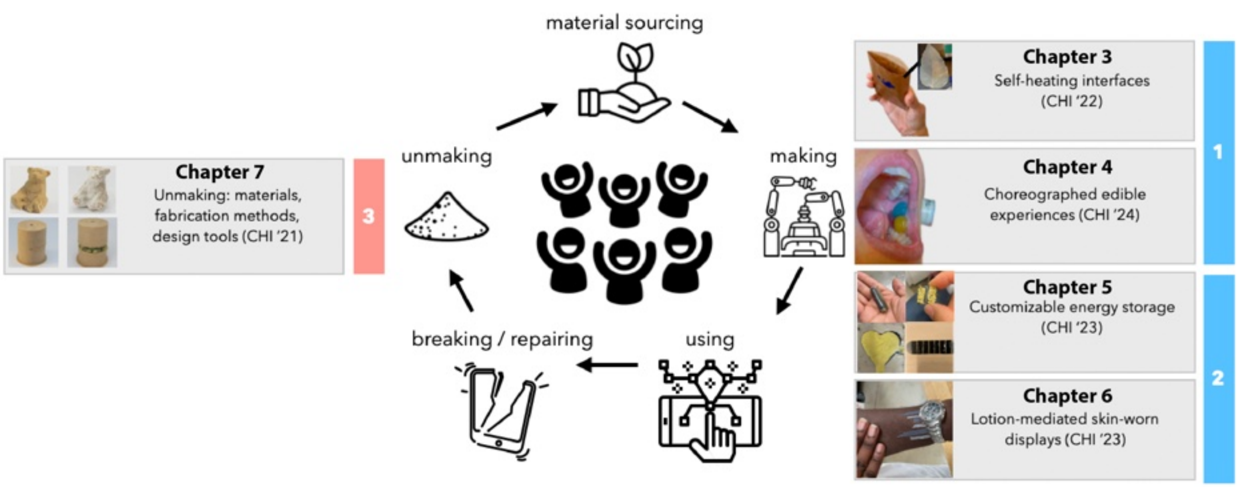


Figure 1.1: Overview of the contributions and projects of this thesis.

Figure 1.1 illustrates the three main contributions and five projects that I present in this thesis. To summarize, the contributions are as follows:

1. a systems-level design strategy for making backyard-degradable systems that leverages wireless energy transfer,

2. a complementary design strategy for making backyard-degradable systems that whereby I build individual backyard-degradable components that can come together to form standalone systems, and

3. a design strategy and framework for unmaking, a design opportunity supported by the use of backyard-degradable materials, that we can “build into” physical systems at the time of initial conception.

I detail these contributions below. Through this making-unmaking presentation, I also show that while imposing the constraint of backyard-degradable materials limits certain aspects of the resulting interactive systems in some ways – namely when it comes to electrical performance and mechanical durability – imposing backyard-degradability as a constraint is also a *constructive* practice. That is, it leads to new degrees of customizability, unique aesthetics, novel interaction paradigms, and the support of unmaking possibilities, among others.

In the next sub-section, I provide an overview of three primary contributions of this thesis.

1.1.1 Making: Wirelessly Activated Backyard-Degradable Modules

The current state of backyard-degradable materials development makes it difficult for completely standalone backyard-degradable systems to meet ideal performance requirements. To overcome current limitations around energy storage and power delivery, I utilize a systems-level design approach to create backyard-degradable systems that are physically separated from but can be wirelessly activated by a durable (non-backyard-degradable) electromagnetic transmitter. The former has the benefit of being able to be disposed of in an environmentally responsible manner, and the latter ideally is either already ubiquitous or can easily be integrated into existing electronics. I provide two examples of systems in Chapters 3 and 4 that utilize this strategy, showcasing the capabilities and range of applications for backyard-degradable systems when we leverage wireless power transfer.

1.1.2 Making: Towards Standalone Backyard-Degradable Systems

The second approach is a materials-centric approach to design individual electrical components – for example, energy storage, displays, and mechanical actuators – with the long-term vision to create standalone interactive systems that are backyard-degradable, power source included, in their entirety. I impose the constraint of using materials that are backyard-degradable, making concessions only when absolutely necessary. This thesis in particular contributes two key components to this toolbox for standalone backyard-degradable interactive electronics: a customizable, energy storage component (Chapter 5), and a lotion-mediated skin-worn display (Chapter 6).

1.1.3 Unmaking

Inherent to backyard-degradability are processes of degradation, decay, and decomposition, which may collectively also be described as *unmaking*. Backyard-degradable materials by nature are transient and will break down in days to months in ambient conditions. These materials thus present a rich design opportunity for unmaking, an extension of progressional ways of making that refers to the dynamic existence of physical artifacts after their originally envisioned use case. While not a moniker for sustainability, unmaking is an ally, potentially prolonging the life of physical artifacts and transforming the otherwise opaque commercial processes of recycling, composting, and degradation into creative processes that the maker community can engage in. Unmaking is a concept that finds philosophical and aesthetic inspiration from multiple art movements, such as Auto-Destructive Art, as well as work in other areas of HCI, such as designing with more-than-human agents, worn media, and slow technology. Unmaking in a literal sense is an intrinsic process that occurs when designing backyard-degradable interactive electronics, but backyard-degradable materials are not in fact a prerequisite for designing with unmaking in mind. Rather, unmaking can be thought of as an equal partner to making that can be forefronted even when designing with materials that are meant to be durable or static. It is a design positionality that, independent of the materials involved, enables us to re-examine conventional notions of making and unearth often neglected political, ethical, and aesthetic aspects of progressional design. This dissertation contributes a foundational framework for how artists, designers, and makers can incorporate and plan for unmaking when drafting and fabricating physical artifacts. In Chapter 7, to demonstrate the generalizability of this framework beyond backyard-degradable electronics, I operationalize its elements and present how unmaking may be integrated into 3D printing workflows as an exemplar.

1.2 Structure

Chapter 2 presents background and prior art that situate backyard-degradable interactive electronics in HCI research in sustainable prototyping, engineering research in degradable electronics, and maker culture. This chapter also outlines terminology – backyard-degradability, electronic interactivity, the everyday maker, making, and unmaking – used throughout this thesis.

As seen in Figure 1.1, Chapters 3 and 4 present backyard-degradable systems that are activated wirelessly by non-degradable electronic transmitters that are already ubiquitous or can be easily integrated into existing electronics. With this systems-level strategy, I demonstrate how we can make backyard-degradable interactive electronics that overcome some of the current limitations in knowledge regarding backyard-degradable energy storage solutions. Chapter 3 describes a wireless Joule heater based on leaf skeletons coated in chitosan and silver nanowires that can be integrated into paper packaging, and Chapter 4 describes an edible interactive system that utilizes focused ultrasound pulses to release sequences of choreographed flavors.

Chapters 5 and 6 present projects that aim to build the toolbox of components for standalone backyard-degradable systems that do not need the non-degradable energy transmitters used in previous chapters. They detail the design, fabrication, and applications of two backyard-degradable electronic components that can be readily made without specialized equipment or materials. Chapter 5 describes *Vims*, a customizable supercapacitor that can be used in place of batteries for low power applications. Chapter 6 describes *Lotio*, a skin-worn electrochromic display that can be powered by *Vims*.

Chapter 7 presents opportunities for planning for the *unmaking* of physical artifacts during the initial design and fabrication phases. Backyard-degradable materials are inherently transient, so *unmaking* becomes both a design opportunity and a necessary consideration when designing with them. Chapter 7 offers a generalizable vocabulary and framework for unmaking as a counterpart to making operations that can be integrated into computer-aided design tools, an exemplar material set, fabrication strategy, and design tool for operationalizing "splitting" and "bulging" unmaking effects for FDM 3D-printed objects as an exemplar.

Finally, Chapter 8 discusses the limitations and future work for backyard-degradable interactive electronics, and Chapter 9 presents a reflection and summary of this work.

1.3 Terminology

Below, I define and explain a selection of key terminology used throughout this thesis. While some concepts may be used and applied differently in alternate contexts, I offer the following clarifications for the context of this thesis.

Backyard-Degradable: *an adjective to describe physical materials that can break down into microscopic parts within a few (<6) months' time in a residential backyard or garden without the need for specialized and controlled composting temperatures, humidity, oxygen content, or microbial activity.*

> To avoid confusion with the industrial standards of biodegradability and compostability, I use the term "backyard-degradable" and, synonymously, "decomposable" to describe materials that can readily break down into microscopic, non-toxic components in ambient conditions without the need for specialized facilities and handling. The American Society for Testing and Materials (ASTM) has several standards for determining whether a material can be labeled "biodegradable" or "compostable" in the United States. The most commonly used standard for allowing such labels on commercial goods is ASTM D6400, which dictates that at

least 90% of a test material should disintegrate into 2mm pieces or smaller after 12 weeks of aerobic composting conditions experienced in industrial composting facilities (i.e. temperature of 58°C, controlled moisture levels, etc.)[2]. Because individual residential composting conditions are uncontrolled and often not as hot or moist as those of commercial facilities, products marketed as biodegradable and compostable often do not in fact degrade in a home or in backyard garden soil. Furthermore, the 2023 BioCycle Residential Food Waste Collection Access Study found that there were only 400 programs in the United States that year that had municipal programs for food waste composting at all, and far fewer of these (roughly half) accepted certified compostable and biodegradable plastics [98]. In this dissertation, I thus use "backyard-degradable" to signify that the materials I use are ones that can indeed degrade, within a few months, into particles not harmful for the environment in largely uncontrolled conditions, as opposed to materials that are certified biodegradable or compostable but in reality most often end up as landfill.

Interactive Electronics: *tangible systems with inputs and outputs whose behavior is governed and activated by the flow of electrons through sub-components that may, upon activation with electrical voltage or current, manipulate the electrical voltage or current in such a way to enact change perceivable to a human.*

I call the systems that are the focus of this dissertation "interactive electronics." The concept of "interaction" is foundational to human existence and has been especially core to the field of HCI from the very beginning. "Interaction" is the subject of a thorough 2019 ACM ACM Transactions on Computer-Human Interaction (TOCHI) journal article by Hornbæk et al., who uncovered 11 themes concerning style in how the word was used across 35 years of CHI proceedings [116]. For the purposes of this dissertation, I use the word "interactive" to broadly describe tangible systems that, given a certain input, produce a perceivable output. I use the label "electronics" instead of simply "systems" to denote that the outputs of the systems I present in this dissertation are specifically activated by the flow of electrons, with the benefits that they can, in certain cases, be used in place of off-the-shelf components in conventional electronics and also benefit from our accumulated knowledge regarding electronic device and system architectures. In contrast, several of the HCI projects cited in the previous section are indeed interactive – using my broad interpretation – but instead use photosensitive dyes, hygroscopic (swelling) materials, or other constituents that, without electrical signalling, directly respond to changes in the environment chemically or molecularly to enact a perceivable output, such as a change in color or shape.

[2] https://www.astm.org/d6400-23.html

The Everyday Maker: *a person who is motivated to create tangible systems who may not have particular expertise, training, or experience with electronics, may not have access to a facility with equipment requiring more than a short (1-2 hour) training session, and may not have access to materials not readily available via scavenging, purchase at a local store, or order from a common online retailer.*

> As discussed earlier in this chapter, fabrication and design research in HCI, compared to research in materials science and traditional engineering disciplines, has prioritized materials that are commercially available and fabrication techniques that are safely and affordably conducted in makerspaces in which any interested party may gain access to with as few restrictions and exclusions as possible. Similarly, the backyard-degradable interactive electronics in this dissertation are consciously designed with this target population, which I call "everyday makers," in mind. This term encompasses people, potentially with little or no expertise with electronics, who simply have the interest and desire to potentially make – by invention or replication – physical artifacts and/or electronics. As will be discussed in Chapter 9, this group actually comprises a wide variety of makers that span many spectra, including education level, access to resources, age, and more. Potential groups include cooks, children, weavers, among countless others. As such, it in practice is potentially impossible to develop design approaches that are universally accessible to every sub-group within the "everyday maker" population. As my perception of what is "accessible" is based on my personal experience and assumptions, the work in this dissertation is admittedly likely inherently tailored to a particular demographic – one that may be largely North American, middle class, and possessing at least a high school education. As backyard-degradable interactive electronics continue to develop, deployed hardware and software toolkits must be increasingly tailored to other groups as well.

Making: *the creation of something new, which may comprise additive processes such as growing and assembly but also subtractive ones, such as cutting and etching.*

> Four chapters of this thesis focus on the *making* of backyard-degradable interactive electronics. By making, I refer to the conventional, "progressional" process of designing physical artifacts and interactive systems, with some end goal and form factor in mind.

Unmaking: *a counterpart to making that refers to what happens after the original goals for an object or system's making are considered achieved, which may also result in the creation of something new, tangible or conceptual.*

Unmaking has been the subject of multiple workshops at CHI ([287, 307]), which I have co-organized, and is the focus of an upcoming TOCHI special issue, which I am a co-editor of. The concept of unmaking is rapidly gaining traction in different sub-communities of HCI, including fabrication, design theory, science and technology studies, and art. Its definition is evolving, diffractive, and multifaceted in nature. For instance, unmaking can be interpreted literally, as a process or sequence of processes involving disassembly, deformation, and decay. It can be enacted by humans, more-than-human agents, or a combination of the two. Beyond its literal definition, we can also unmake intangible concepts or ways of doing; unmaking can be interpreted as not only a process or sequence of tangible actions but also a design positionality and philosophy that allows us to re-examine sociopolitical and ethical assumptions and consideration of progressive design and making, creating space for new possibilities. In addition to unmaking physical artifacts, we can also unmake intangible concepts or ways of doing. In the context of this dissertation, Chapter 7 builds a framework for tangible unmaking and offers strategies for how unmaking can be forefronted during the initial design of physical artifacts. This dissertation as a whole also philosophically *unmakes* conventional electronics design, uplifting everyday materials as active electronic elements, challenging notions of performance requirements and specifications, and inviting alternative participants in the design process.

1.4 Statement of Multiple Authorship and Prior Publication

This dissertation draws upon work previously published at ACM conferences, including CHI 2021 (*Unmaking*, Song and Paulos 2021 [304]), CHI 2022 (*Towards Decomposable Interactive Systems*, Song et al. 2022 [308]), CHI 2023 (*Lotio*, Song and Dierk et al. 2023 [306]; and *Vims*, Song and Paulos 2023 [309]), UIST 2023 (*Decomposable Interactive Systems*, Song 2023) [303], and CHI 2024 (*Füpop*, Song et al. 2024 [305]). While I served as first author and led the research and writing behind each chapter in this thesis, much of the work was highly collaborative. For example, the work for *Towards Decomposable Interactive Systems* was conducted during a summer internship with Accenture Labs, where several colleagues, including Aditi Maheshwari, Eric Gallo, Taylor Tabb, and Andreea Danielescu, assisted in ideation, paper editing, and documentation. *Lotio* was originally conceived of by Christine Dierk, who developed the very initial prototypes, ran the user study, and co-first-authored the resulting paper. Szu Ting (Cindy) Tung also provided invaluable assistance for *Lotio* by exploring alternative fabrication methods to make more aesthetic and functional prototypes. Cindy Tung and Alexis Kim helped in the exploration of spherification techniques and documentation of prototypes for *Füpop*. *Unmaking* is a concept that has been the subject of two CHI workshops that I have co-organized (*Sustainable Unmaking*, Song et al. 2024 [307] and *Unmaking@CHI*, Sabie et al. 2022 [287]) and has been developed in conjunction with the workshops' co-organizers and participants.

Chapter 2

Background

In this chapter, I situate this dissertation in relation to bodies of research in degradable electronics in engineering, sustainable materials in HCI, and maker culture.

2.1 Anatomy of Interactive Electronics

As discussed in Chapter 1, electronics have become ubiquitous in our everyday lives. An interactive electronic system may consist of thousands of individual parts, but on a high level, the most basic system may be abstracted into a few parts, as shown in Figure 2.1.

On the outside there is an enclosure, which is often made of plastic. Inside that, there is an

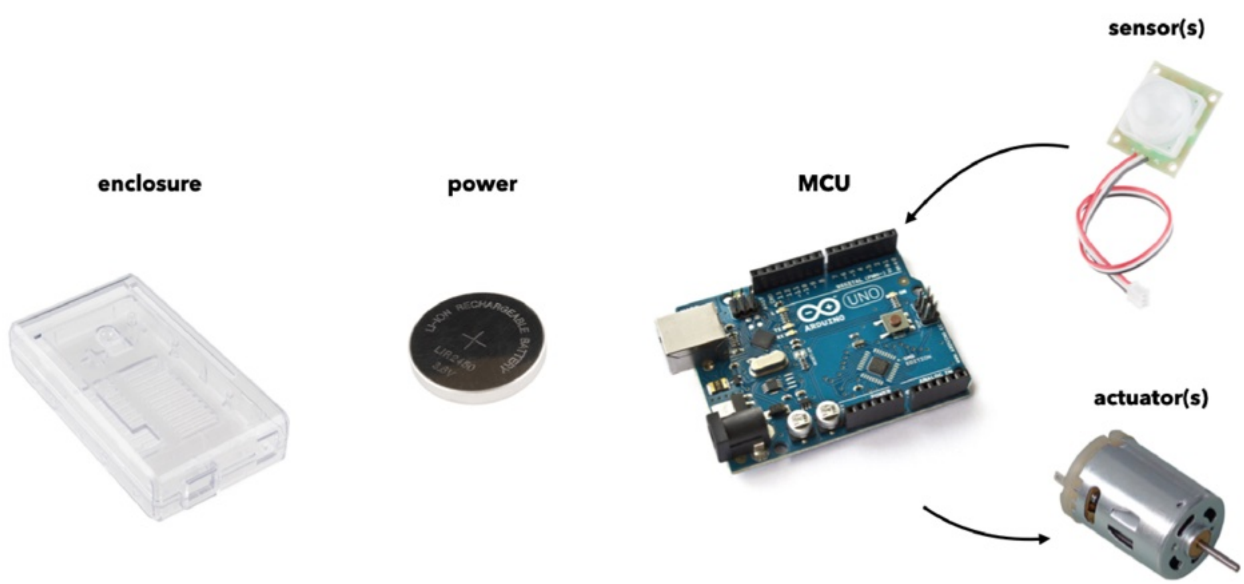


Figure 2.1: Basic anatomy of an interactive electronic system.

energy storage module that provides power to the other electronic components. The "brain" of the system is a microcontroller unit, which is a silicon-based integrated circuit. The microcontroller processes input data from sensors, such as photoresistors or touch capacitive sensors, and uses it to modulate outputs, such as a mechanical motor or a display. Currently, each one of these components is conventionally made from elements and materials that do not readily degrade in the environment. Thus, at the end of a device's life, these parts must be separated and individually recycled or reused. Unfortunately, the United Nations Institute for Training and Research's 2024 Global E-waste Monitor reported that only 22.3% of e-waste mass was collected and properly recycled in 2022 and projected that this rate would continue to decrease [174]. Furthermore, the mass of e-waste generated every year is greatly outpacing the documented mass of e-waste being recycled, with 62 million tons being generated in 2022 – an increase of 82% since 2010 [174].

While mitigating this issue will require a multi-faceted approach involving governmental regulations and drastic changes in consumer behavior, it is also clear that we need new technologies that use alternative materials and components that can easily and benevolently degrade in the environment, without contributing to the accumulation of waste that takes up valuable space and makes the soil less livable for both humans and other organisms. As will be discussed in the subsequent section, starting in the late 2000s, researchers across disciplines, from traditional engineering disciplines to HCI and design, have recognized the dearth of easily degradable materials, electronic components, and systems that could potentially replace traditional, non-degradable electronics, and they have been actively responding to this call.

2.2 Related Work

In this section, I provide an overview of the recent burgeoning of research in degradable electronics from traditional engineering disciplines and research in more accessibly fabricated materials from HCI and design. I also discuss the role of "everyday makers" in sustainable technology design in terms of their historical and current activities as well as opportunities. Chapters 3-7 each provide an additional expanded review of related work related to specific contributions of that chapter.

2.2.1 Degradable Electronics

This thesis is by no means the first to address the question of how we make easily degradable electronics. In the past decade especially, researchers across multiple disciplines have actively been searching for new materials to make electronics "green" [191]. Some of these efforts are illustrated in Figure 2.2. The resulting nascent designs have been posed as a future alternative to conventional electronics to mitigate the accumulation of e-waste and also as a useful tool for transient applications in medicine, environmental sensing, and security [320]. Several researchers across materials science, electrical engineering, and mechanical engineering have investigated and characterized materials such as paper [328, 272, 273, 51, 35], chitin [136], and silk [322] for substrates and encapsulation materials. Researchers have also reported the use of thin films of silver nanowires (Ag NWs) [120], carbon nanotubes [120], iron [389], magnesium [389], or conductive polymers such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) [189] to make electrodes that readily biodegrade into non-toxic particles. By combining conductors that are environmentally benign in small quantities and semiconducting conjugated polymers and other organic materials, researchers have developed transistors, sensors, light-emitting devices, and more [320].

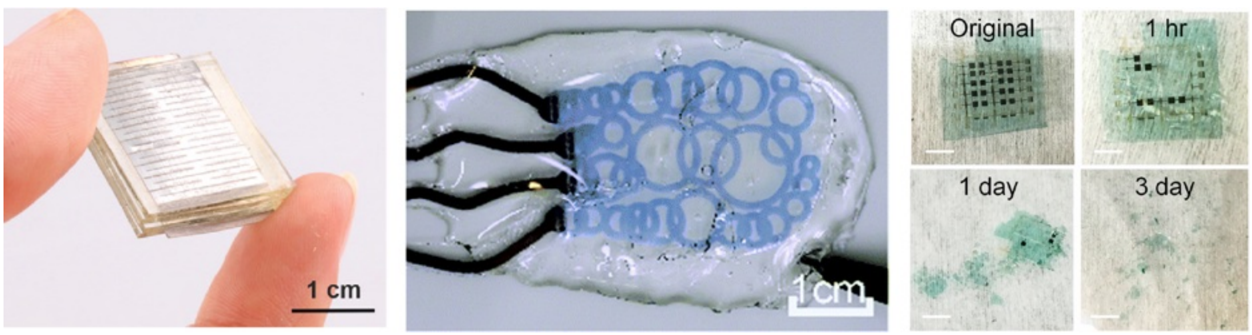


Figure 2.2: Materials science and engineering researchers have developed easily degradable electronic components in the lab that can be used for transient electronics, among other applications. For example, from left to right: a battery comprising Mo/MoO_3 and Mg electrodes and a calcium alginate electrolyte [150], an electrochromic display display [266], and disintegrating transistors on a cellulose substrate [186].

Easily degradable supercapacitors have also been demonstrated as a way to store energy for the resulting devices [77, 141, 27, 212, 119, 194, 384, 2, 357]. Under arguably the most intense investigation is the search for biodegradable semiconducting materials, which are necessary to replace conventional integrated circuits. However, meeting performance standards set by non-degradable electronics, which is an implicit goal of most research in green electronics, is immensely difficult. Novel materials that have been developed thus far require highly specialized processes conducted under tightly controlled laboratory conditions and with specially designed, expensive equipment. Nonetheless, these efforts are certainly important for the future of biodegradable systems, and as processes are optimized and adapted for larger scale manufacturing, they may become more widely available, stable, and accessible.

2.2.2 Sustainable Materials in HCI

While the aforementioned work has led to devices with increasingly impressive performance, they generally utilize some expensive and toxic materials, such as nano-engineered materials and acrylamide [212, 119, 384, 2], or specialized processes, such as high-temperature heating under inert or vacuum conditions [27, 212, 384]. These cannot be simply ported into a home kitchen, community space that does not require special training or safety precautions, or other accessible fabrication environment. Whereas the focus in traditional engineering disciplines has been on the novelty of materials and the performance of the resulting devices, the focus within the HCI and design communities has been on leveraging safe, low-cost, and widely available materials and fabrication workflows. HCI researchers have called for more sustainable prototyping and design practices for over a decade [28, 213, 182, 33, 72, 265]. Laudable efforts have been made to propose and integrate practices such as upcycling [40] and "salvage fabrication," [66] into fabrication workflows to prolong the life of physical artifacts through reuse and thus reduce waste. Wu and Devendorf similarly presented explorations for designing smart textiles that were woven to enable unraveling and reconfiguration [381].

When it comes to selecting materials for their designs in the first place, Lazaro et al. highlighted the importance for makers to minimize the "embodied energy" and associated carbon dioxide emissions over their selected materials' entire lifecycle [182]. In the last few years, there have been several commendable and provocative demonstrations of "bio-design" resonating with this call, highlighting and utilizing the aesthetic and functional capabilities of natural, easily-degradable materials [39, 151, 21]. Researchers have 3D printed conductive structures from salty food items like Vegemite and Marmite [108]. Conductive traces have even been made by lasing wood and other carbon-rich substrates with a de-focused laser cutter, creating graphene [132, 49]. In some cases, living organisms that change shape or color may be utilized in lieu of some electronic components [386, 151, 253, 105, 261]. One material that has become particularly popular in the last decade and is capable of being grown by an amateur maker is mycelium, the vegetative root structure of fungi. It is easy and quick to grow, has desirable mechanical properties, and is readily compostable. Designers have grown mycelium into various functional objects and proposed it as a viable replacement to plastic in many applications [152, 339, 340, 367, 104]. Mycelium has been explored as a valuable material for integration with electronics (Figure 2.3). For example, Lazaro et al. have demonstrated that grown mycelium forms may be milled and shaped to incorporate electronics such as batteries and LEDs [339, 340], and Weiler et al. and Gough et al. have shown how mycelium may even be made to grow conformally around electronic components embedded during the mycelium growth process [367, 104].

These mycelium-based hybrid electronics systems are certainly a big step towards the sustainable prototyping and manufacturing of electronic and interactive systems. However, while mycelium is backyard-degradable, the embedded electronics are not. They may be reused, but they must first be manually separated from the mycelium. Additionally, once they have reached the end of their life, their disposal is still problematic. Complete interactive systems with these material innovations still use non-degradable wiring, batteries, microcontrollers, and/or substrates to varying degrees. Individual research papers often focus exclusively on developing green alternatives for one electronic component – or sometimes just a single material layer of a component – resulting in provocative findings but still leaving questions around the feasibility of fabricating fully backyard-degradable electronics unanswered.

Figure 2.3: Mycelium has emerged in HCI as a popular material that can be grown and readily decomposed in backyard soil. It can be shaped and used as a substrate for conventional electronic parts. From left to right: mycelium wearable with decorative LEDs [340], mycelium clock [367], mycelium flower pot with an integrated moisture sensor and LED indicators [104].

2.2.3 DIY Culture and Sustainability

There is a rich history in HCI of developing technologies to support hobbyist makers and electronicists who have limited access to specialized materials and fabrication facilities [175]. Broadly speaking, I speak of a "maker" as someone who is already inclined to create things, specifically tangible ones, – this will be discussed more in the Terminology section of this chapter. The "Do-It-Yourself" (DIY) fabrication methods that such makers rely on utilize low-cost and widely available technologies such as screen- and inkjet-printing [176, 154] and easy-to-use hardware toolkits such as Arduino development boards. With such approaches, non-expert makers (i.e. those without an engineering degree or with a limited number of years of experience prototyping with electronics) have successfully made a wide range applications, such as in assistive technologies [124, 223], devices for biology [84], e-textiles [34, 36], cell phones [224], and home electronics [289]. In addition to prototyping with commercially available hardware kits, makers scavenge materials from the world around them, for example pairing potato slices, or even whole potatoes, with copper and zinc electrodes to make batteries [97, 1].

While one might argue that the development of new technologies should prioritize a path to mass production and commercialization to achieve greater impact, focusing on the time being on catering to the "maker community" and DIY-friendly methods and materials can generate unforeseen applications, design considerations, and other factors that are valuable for future research and, ultimately, also commercial product development. Although they are more laborious than simply ordering pre-packaged, commercial goods, DIY approaches have been touted as democratizing technological engagement, empowering makers, fostering emotional attachment, and increasing engagement with nature, among other benefits

[321, 124, 209, 91]. DIY material development in particular has also been shown to provide valuable opportunities for personal expression and experiential learning [283, 256, 21]. Participatory design workshops that study technologies in the hands of non-traditional makers, including children [286] and under-resourced communities [350], and have similarly revealed unexpected design opportunities, considerations, and use cases.

Figure 2.4: A selection of DIY-friendly electronics made from scavenging food, e-waste, and other accessible materials. From left to right: battery made from a potato with copper wire and iron nail electrodes (David R. Tribble), robotic chair made from parts from a hoverboard [210], and drill with battery pack with parts scavenged from an e-waste recycling center [350].

Makers are increasingly sharing their discoveries and prototyping workflows on online platforms, such as YouTube [43, 178, 243, 311], allowing hobbyists to take more control over their electronics designs and get more inspiration from others with a simple web search. When it comes to sustainable technologies in particular, however, options for non-expert electronicists are limited. The degradable electronics that engineering and materials science researchers are working on often cannot be ported outside a cleanroom or laboratory environment. As previous mentioned, makers often support sustainable practices by scavenging and reusing materials around them, including food items, and while these have resulted in creative and inspiring devices and systems, as seen in Figure 2.4, they are generally not flexible in form factor (sometimes also function), and they still rely on non-degradable parts, such as nails and conventional electronic components. Furthermore, while solar cells, piezoelectric generators, and miniature wind turbine kits are commercially available, these components are not necessarily accessible in all locales, and they still require some technical knowledge to select, spec, use, and repair. Researchers have developed software design tools to help non-expert electronicists navigate the complex process of using such components [258], and continued work in this area will certainly help makers leverage energy harvesters and off-the-shelf components for developing more sustainable electronics. Nonetheless, there is still a need for more types of sustainable hardware, especially hardware that makers can create themselves.

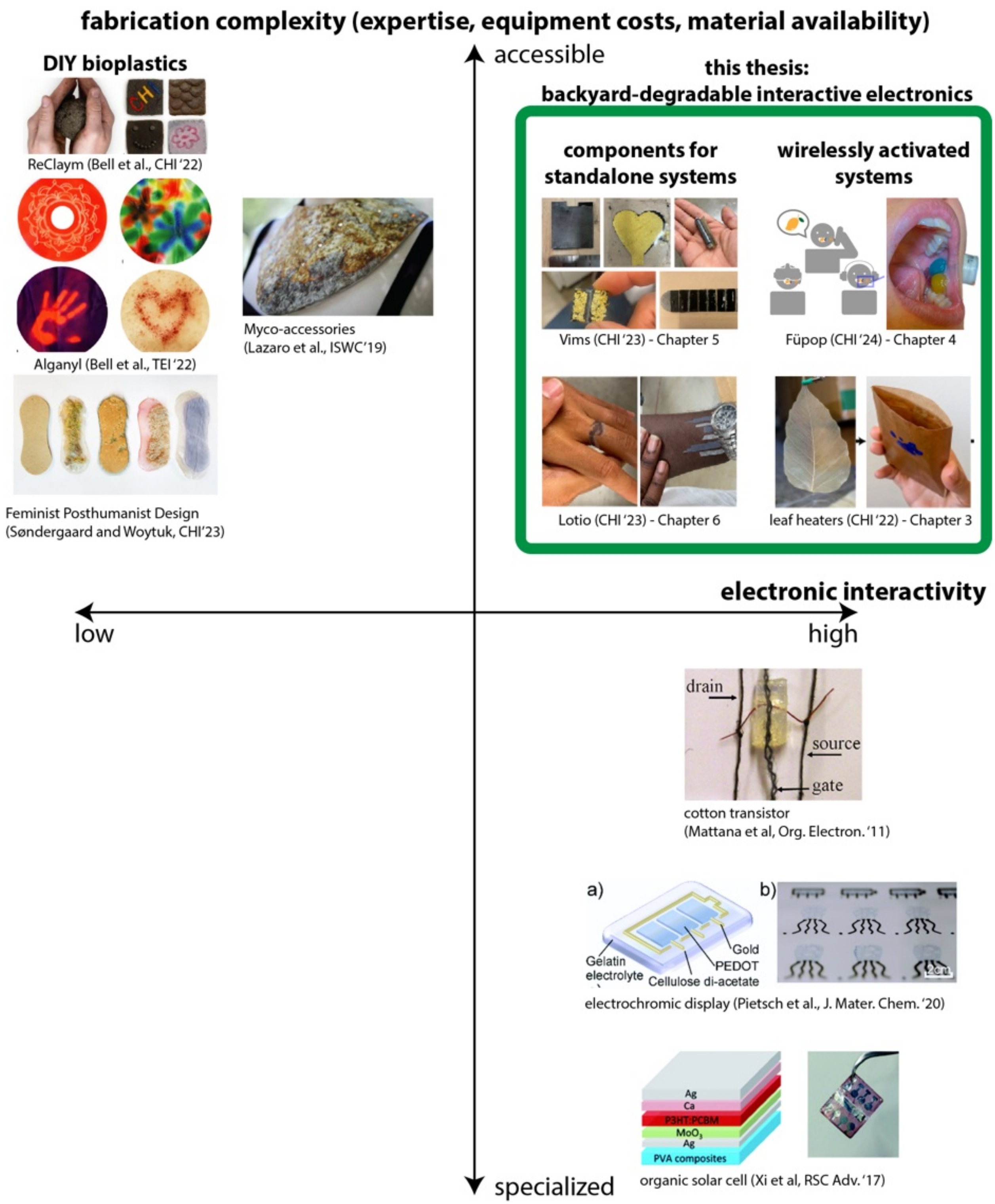


Figure 2.5: Backyard-degradable interactive electronics maintain low fabrication complexity, seen in the HCI literature, while achieving high electronic interactivity, seen in materials science and engineering literature.

2.3 Backyard-Degradable Interactive Electronics

This work in this dissertation is situated at the intersection of the aforementioned research in degradable electronics in traditional engineering disciplines, sustainable material exploration in HCI, and DIY culture. As illustrated in Figure 2.5, the backyard-degradable interactive electronics that this thesis presents aim to combine the low fabrication complexity that is a priority in design and HCI literature with the high electronic interactivity of degradable electronics seen in the engineering research literature. The prior work represented in Figure 2.5 provides only a small sample of published systems, devices, and materials, many of which were illustrated and discussed in more detail in the Related Work section of this chapter. This dissertation focuses on the development of backyard-degradable interactive electronics that utilize low cost and widely available materials – including bio-based and natural ones where possible – that can be packaged together in future hardware toolkits for deployment in participatory design workshops with communities of “everyday makers.”

Chapter 3

Leaf Skeletons for Wireless Joule Heating

Figure 3.1: From leaf skeletons (left), I create a lightweight packaging that can wirelessly heat its contents (center) and is fully backyard-degradable (right).

In this chapter, I present the design of an interactive electronic system, activated wirelessly, whereby a standalone module comprises components that are entirely backyard-degradable (Figure 3.1) [1]. I leverage the inherent material properties of natural materials, such as paper, leaf skeletons, and chitosan, along with silver nanowires to create a new system capable of being electrically controlled as a portable heater. This backyard-degradable system, capable of wirelessly heating to over 70°C, is flexible, lightweight, low-cost, and reusable, and it maintains its functionality over long periods of heating and multiple power cycles. I detail its design and present a series of use cases, from enabling a novel resealable packaging system to acting as a catalyst for shape-changing designs and beyond. Finally, I highlight the important backyard-degradable property of the interactive system when it meets end-of-life.

[1] Large portions of this chapter have previously appeared in the 2022 ACM CHI proceedings. The original citation is as follows. Katherine W Song, Aditi Maheshwari, Eric M Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards backyard-degradable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22). Association for Computing Machinery, New York, NY, USA, Article 100, 1–12 [308].

3.1 Introduction

As the demand for material goods increases, waste is accumulating on our planet at an alarming rate. Electronics in particular present significant sustainability challenges due to the energy-intensive processes involved in their production and their dependence on non-renewable resources. Amidst the looming threats of climate change and ecological crises, reducing and circularizing material consumption has become a prominent priority for both commercial electronics manufacturers and across multiple research disciplines. This thesis presents backyard-degradable interactive electronics as one approach to help this mission. However, as discussed in Chapter 1, it is not possible to make certain high-speed or precise electronic systems with degradable materials, nor is it necessarily desirable to have every electronic system degrade quickly. Nonetheless, there exists a space of "semi-permanent" technological design that biological, backyard-degradable materials are well-suited for. For example, packaging for food, cosmetics, and other goods is one application area that demands both reusability and responsible disposability, and this is the focus application of this chapter. Increasingly eco-conscious consumers wish to be able to reuse packaging when possible, but packaging inevitably becomes soiled or worn beyond recovery, or it simply becomes overly burdensome to carry in certain on-the-go situations. At the same time, there is a growing demand for smart and interactive packaging that can monitor or regulate temperature for food safety, detect and alert a user of unsafe microbial growth, or indicate prior tampering that might have compromised the packaging's contents [294]. While backyard-degradable packaging made from paper, chitosan, silk, and other renewable materials currently exists, this demand for smart packaging poses an added challenge. The non-degradable electronics that are conventionally considered necessary leave consumers with limited choices that are undesirable. People may throw away the smart packaging when it becomes inconvenient or unusable and bear the ethical weight of creating electronic waste; they may deconstruct the packaging to separate any biodegradable or compostable parts from the electronics, which then need to find a second use; or they may keep the packaging for as long as possible, even after it becomes unsanitary or nonfunctional.

In this chapter, I impose an early design limitation that all materials be backyard-degradable and present packaging augmented with basic heating functionality as an example application. I detail the design of a lightweight, reusable packaging for heating food or cosmetic items using natural and off-the-shelf materials. The packaging design, which is backyard-degradable in its entirety, integrates thin heating elements made from leaf skeletons that can be activated wirelessly without the need for embedded discrete electronic components. I propose an extensible design approach usable beyond packaging that forefronts the use of easily degradable materials from the beginning instead of finding biological analogues for non-renewable components in already existing system designs. I present my main contributions as follows:

- Design and evaluation of a fully backyard-compostable heating packaging that is wirelessly powered, resealable, and capable of indicating product readiness with thermochromic inks

- Proposal of a materials-first product design process that prioritizes the use of biological structures and natural materials to create a wide range of interfaces that are "semi-permanent" but backyard-degradable

3.2 Related Work

3.2.1 Heat as an Interactive Material

While there are many valid applications to choose from to demonstrate backyard-degradable, semi-permanent electronics, in this chapter, I focus primarily on one: self-heating packaging. Heaters are fundamental elements of many products that people rely on and interact with daily. In addition to being essential to maintaining a comfortable indoor temperature, cooking, and fulfilling other fundamental needs in the home, heaters are common elements built into portable systems, such as drink warmers and on-body therapy pads. Heat has also been explored as a design resource for affective feedback [326, 335, 374, 375, 373, 372], navigational cues [325], new aesthetic experiences [139], the communication of social presence [101, 102, 184, 185], and the augmentation of other sensory cues to assist individuals with certain impairments [79, 127].

There are several ways to induce heating. One method commonly used in portable products today is based on an irreversible exothermic reaction, such as the oxidation of a metal. Constituents, such as magnesium or iron filings, are packed into a sealed sub-compartment within a larger package, and an individual may activate an exothermic chemical reaction by adding water or exposing the compartment to air. Products relying on this include hand warmers and *Meal, Ready-to-Eat*s (MREs). Downsides of systems like these include bulkiness (from the extra chemical components and packaging to initially isolate them) and non-reusability. A second popular method for integrated heating is through Joule (resistive) heating. In this modality, electrical potential is applied across a resistive element, and the resulting current causes energy to be dissipated as heat. Clothing irons and conventional electric stove-tops are examples of commercial products based on Joule heating. Such systems, even when they are portable, also tend to be bulky, relying on portable batteries and hefty metal wiring. There are also biological processes that produce heat as a byproduct, such as fermentation and composting. These have been demonstrated as potential solutions for building-scale heating [88] but have not been utilized for smaller-scale or portable applications.

3.2.2 Degradable Materials

Chapter 2 presented research across HCI and traditional engineering disciplines related to a wide variety of passive and active materials for making bio-degradable interactive systems. Most relevant to this work is the research of Sharma et al., who demonstrated a process for coating leaf skeletons with silver nitrate and, subsequently, Ag NWs to make small, biodegradable heating patches capable of boiling a vial of water [297]. Leaf skeletons coated with Ag NWs have subsequently also been found to be viable options for pressure sensors [169] and fog harvesters [296]. As I will describe in the Fabrication section, I was unable to use Sharma et al.'s exact method of making leaf heaters to reliably build components robust enough to withstand repeated and prolonged use, but this work was foundational to the demonstration I present here.

3.3 Heater Design Considerations

Among the aforementioned heating schemes, I chose Joule heating as the basis for this system. Joule heating refers to the effect of current flowing through an electrical resistor to create thermal energy (heat). The amount of heat that is produced per second (power) is proportional to the square of the amount of current times resistance. In addition to allowing the system to be reheated multiple times, Joule heating requires very few components, simplifying the number of components to be developed. A basic Joule heater comprises 2 parts: a power source, conventionally provided by portable battery or via a power cord to a wall outlet, and a conductive large-area heating element, conventionally made from copper or Nichrome (nickel-chromium alloy) wires arranged in a mesh or serpentine pattern.

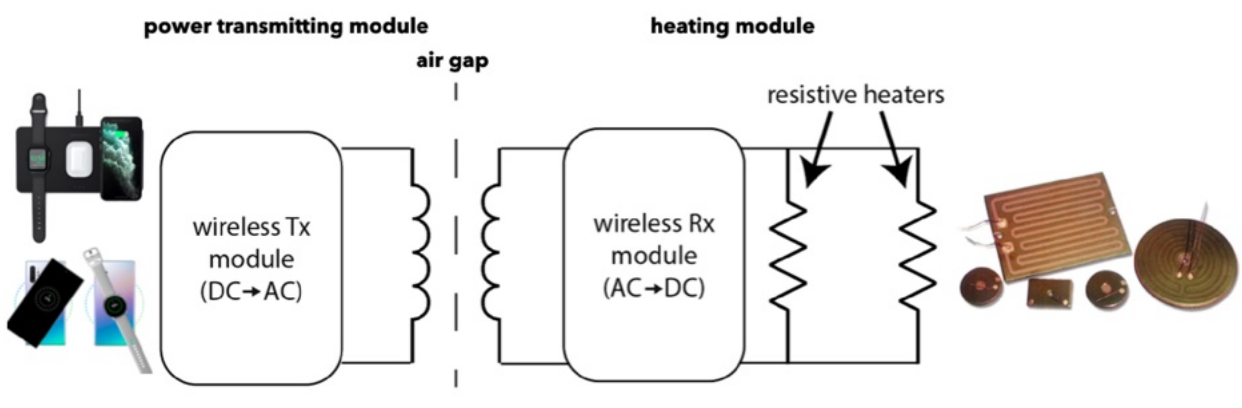


Figure 3.2: A schematic of a wireless Joule heater made with conventional electronic materials and devices.

Batteries and contact-based interconnects are not easily made with backyard-degradable materials, so I eliminated these as possibilities for my design. I identified the most promising alternative to be wireless power transfer. The electrical schematic for a wireless Joule heater with conventional electronics is shown in Figure 3.2. Wireless chargers are commercially available and quickly becoming ubiquitous in homes, vehicles, offices, restaurants, and other locations for charging electronics on-the-go. There are even some mobile phones available on the market today that can be transformed into a wireless charger, allowing wirelessly-powered interfaces like ours to be truly portable and usable virtually anywhere. In a typical wireless charging system, a transmitter circuit creates an alternating magnetic field by generating alternating current (AC) through a conductive coil. This magnetic field in turn induces an alternating current in a receiver coil that is aligned with and placed near the transmitter coil. Typically, the receiver end contains a circuit of discrete electronic components such as rectifiers and capacitors to filter and convert the AC signal into direct current (DC) for charging applications. However, because the primary design goal was to create a fully backyard-degradable system, I eliminated the use of such components as an option, requiring that the system be able to operate on AC power. This allowed the circuit to be integrated into the packaging to be very simple.

Finally, for the heating element, conventional Joule heaters are made with metal traces that are patterned to evenly distribute heat over a given area. The pattern is usually created either by a mechanical shaping process (if using bulk wires) or a subtractive wet or vapor-based chemical etching process (if starting with a planar metal foil or thin film). As I describe in the upcoming section, to replace these materials and processes, I looked to nature — specifically tree leaves — to find an appropriate area-covering structure.

With these considerations and design decisions in mind, I next detail the design of the system.

3.4 Design of Backyard-Degradable Heater

3.4.1 System Overview

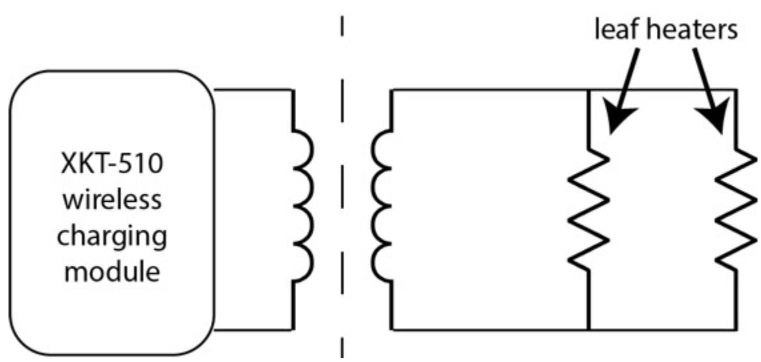


Figure 3.3: Schematic of heating packaging. Compared to Figure 3.2, active circuitry elements have been removed, and leaf heaters replace conventional resistive elements.

The electrical schematic of the system is shown in Figure 3.3. As previously mentioned, by powering the system wirelessly with AC power, I simplify the circuit to allow us to successfully create it with backyard-degradable materials. The circuit on the packaging design contains only resistive elements in the form of leaf heaters, whose fabrication is detailed in the next section; non-toxic, compostable conductive ink; and a receiving coil, which may be patterned with the same ink.

I used an off-the-shelf XKT-510 IC-based wireless charging module ($4USD) to power and test the heating packaging. The amount of power delivered, and thus the amount of heat generated, may intentionally be varied by adjusting the position of the receiving coil on the packaging relative to the transmitting coil of the wireless charging module. When the coils are aligned on top of each other with virtually no spacing between them, the system can achieve maximum heating. To achieve lower temperatures, the package may be moved side to side or elevated above the charging module.

Next, I discuss the selection of the materials and the fabrication of the system.

3.4.2 Material Choices

3.4.2.1 Interconnects

There are several options for backyard-degradable conductive inks to connect heating elements and pattern a wireless receiving coil. Here, I use a commercially-available, highly conductive, and water-based silver ink certified to be non-toxic (Circuit Scribe) [284]. Other backyard-degradable conductive inks, such as Copprint's Nano Copper [300], metal oxides, and conductive carbon inks may also be used [191].

3.4.2.2 Heating Element: Substrate

Crafting the heating element itself is more challenging. For this, I take advantage of one of nature's branching structures: tree leaves. As leaves grow on trees, their veins branch out in a fractal pattern to cover relatively large areas, naturally accomplishing patterns similar to those in conventional Joule heaters. Leaf skeletons comprise the network of veins and structural components of natural leaves that are left behind after the soft, fleshy parts have decomposed or have been eaten away. They may also be prepared at home by soaking leaves in a washing soda and water solution for roughly 2 hours [292]. Different trees produce skeletons with differing fractal patterns that could be strategically selected depending on the desired application. I initially experimented with un-dyed *Ficus religiosa* (bodhi) leaf skeletons as well as *Ficus elastica* (rubber tree) leaf skeletons from the Nava Chiangmai shop on Amazon.com. I did not find a notable difference in performance or reliability between heaters made with these two species so decided to continue solely with *Ficus religiosa* leaf skeletons, which were easier to cut into regular squares of a desired size due to their larger size and less obtrusive central stem compared to the *Ficus elastica* leaf skeletons.

3.4.2.3 Heating Element: Conductor

As the conductor, I used off-the-shelf Ag NWs from Sigma-Aldrich to form a thin coating over the substrate. Ag NWs in low concentrations are considered to be non-toxic and biodegradable and have gained attention for a variety of electronic, opto-electronic, and biomedical applications [82, 329, 192]. Ag NWs may be synthesized in a variety of ways, including via "green" methods that do not require toxic solvents or reagents [82, 198].

3.4.2.4 Heating Element: Stabilizer

Before the application of Ag NWs, however, the leaf skeletons must be coated in chitosan to form an all-natural substrate for the Ag NWs. Chitosan is a natural material from shellfish waste that is an attractive candidate for a myriad of applications due to its low cost, bioavailability, biodegradability, and biocompatibility [12]. This combination of leaf skeletons and chitosan is necessary to make stable heaters, as each one individually has failure modes that prevent them from acting as a reliable heater substrate. Sharma et al. demonstrated small leaf heater patches without a stabilizing overcoating like chitosan. However, I found that when attempting to make larger-area heaters needed for packaging and other functional applications with the reported method, electrical current usually concentrated at a small point on the leaf, eventually burning through the structure and rendering the leaf heater unusable, as seen in Figure 3.4. The leaf skeleton itself is still critical, however. As Figure 3.4 shows, a smooth, untreated chitosan film dipped in Ag NW solution results in a non-uniform Ag NW layer that is not continuously conductive across the sample and thus not functional as as heater. In summary, chitosan acts to stabilize the leaf skeletons while they are heated, and the leaf skeletons provide an underlying texture and pattern for the Ag NWs to adhere to.

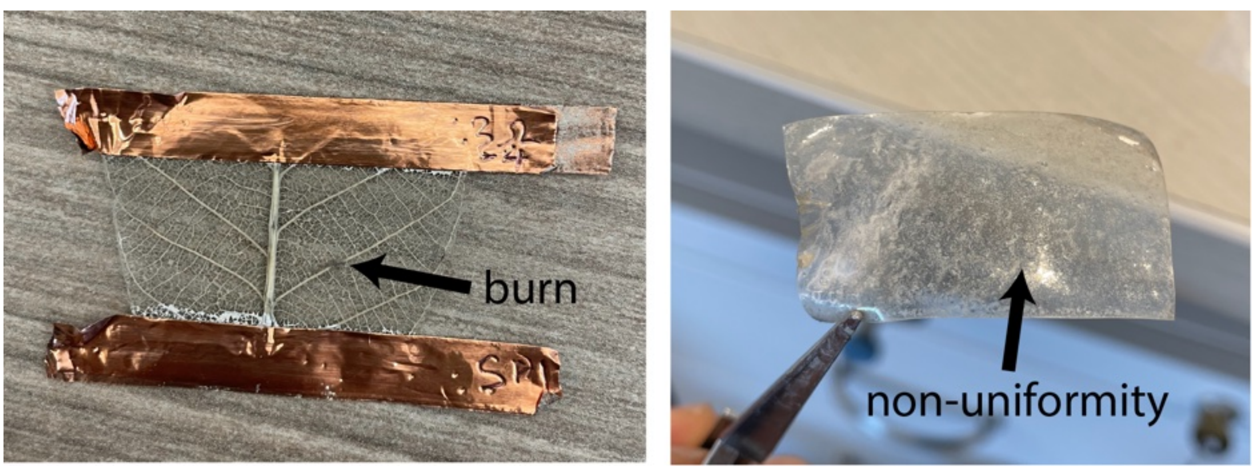


Figure 3.4: Left: An Ag NW-coated leaf skeleton without chitosan burns and becomes non-operational very easily upon heating. Right: An Ag NW-coated chitosan film without a leaf skeleton or other texture for the nanowires to adhere to is not uniformly conductive.

Leaf skeletons and chitosan are extremely cheap, with the quantity used for a 7.6cm x 7.6cm leaf heater amounting to a few US cents. I purchased Ag NWs from Sigma-Aldrich for $235 for 25mL. As Ag NWs become more popularly used, I expect their cost to drop, but even as-is, the amount of Ag NWs loaded on each leaf heater amounts to a mere 50 US cents.

3.4.3 Fabrication of Leaf Heaters

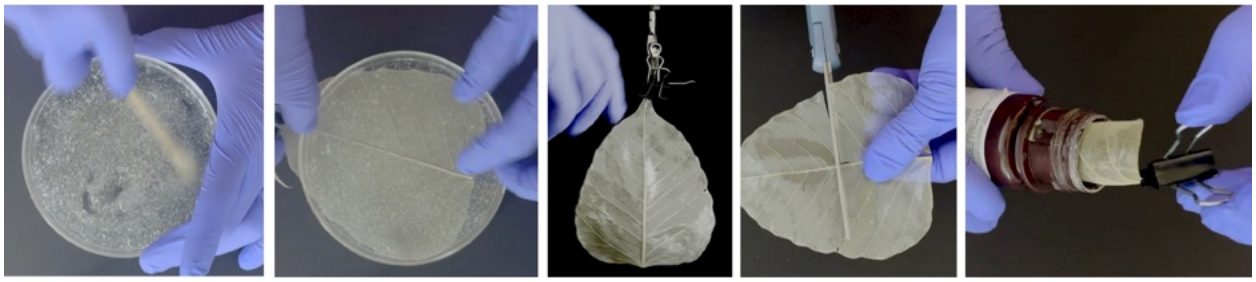


Figure 3.5: Fabrication process of leaf heating elements. From left to right: a chitosan jelly is stirred by hand, a leaf skeleton is dipped into the jelly, the leaf is hung to dry, the leaf is cut by hand with scissors into patches, and then the leaf is dipped into a silver nanowire solution.

The fabrication process, illustrated in Figure 3.5, for making the core leaf heater elements is straightforward and does not require specialized equipment. First, a chitosan jelly is prepared by mixing dried chitosan powder (medium molecular weight) into a 2% acetic acid solution (v/v) for 1 hour. Glycerol is then added as a plasticizer in a 0.4:1 glycerol:chitosan weight ratio and mixed for an additional 30 minutes. All materials are purchased and used as-is from Sigma-Aldrich. Next, *Ficus religiosa* leaf skeletons are dipped in the chitosan solution and hung to dry for 4 hours. The resulting substrates largely retain the texture and aesthetic of the underlying leaf skeletons (Figure 3.6).

Once dried, the leaves are cut into 7.6cm x 7.6cm pieces and dipped into an Ag NW solution (0.5mg/mL in ethanol) for 20 seconds. They are then once again hung to dry for 10 minutes at room temperature (Figure 3.6). At this point, they are ready to be integrated into a system. As my main example, I describe the next steps to create interactive packaging that wirelessly heats its contents.

3.4.4 Assembly of Packaging

The prepared leaf heaters are mounted onto the adhesive side of paper tape that has a natural rubber adhesive. For greater area coverage, I connect leaf heating elements in parallel. They are connected via water-based, non-toxic silver ink by using a stencil and brushing the ink onto the substrate by hand. The assembly is then simply adhered onto a kraft paper bag, as seen in Figure 5.4.

On the reverse side of the kraft paper bag, traces are patterned for wireless power receiving. Wireless receiving antenna designs are well established and typically consists of concentric rings or antenna lines for the reception of wireless power. This can readily be done with silver ink or Ag NWs themselves using techniques such as ink-jet printing [274, 190, 85] and transfer-printing [396]. Here, as a proxy and for prototyping simplicity, I use

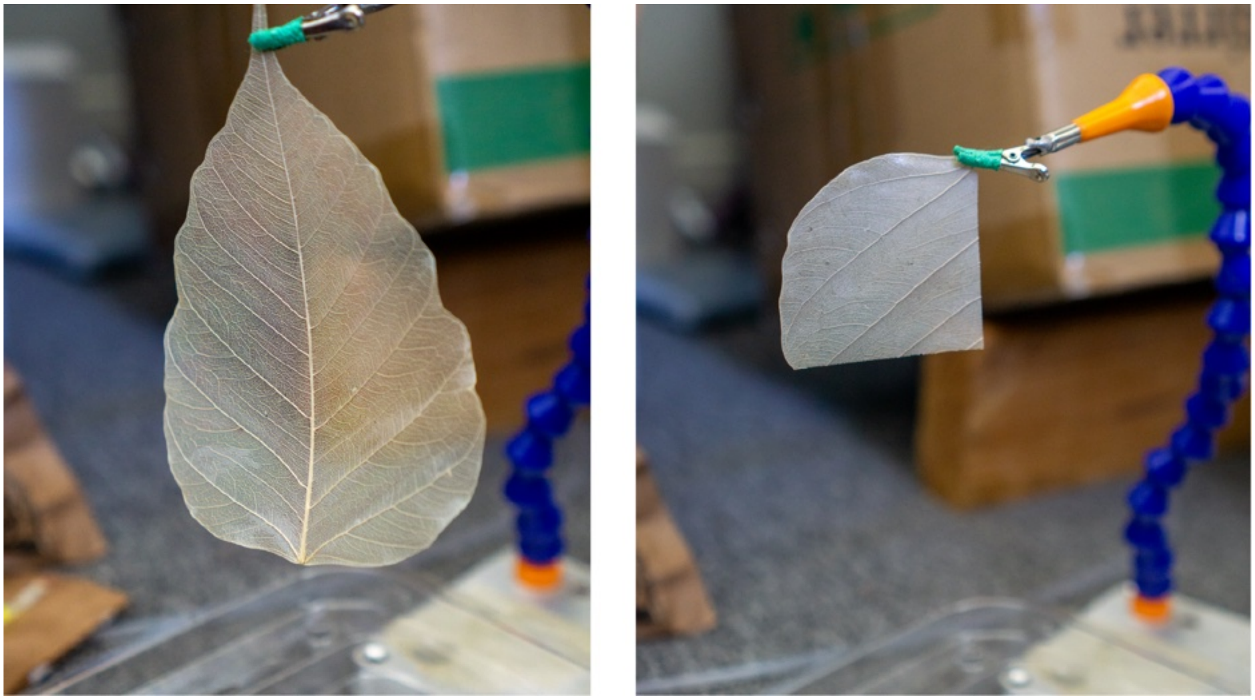


Figure 3.6: Left: *Ficus religiosa* leaf coated in chitosan. Right: section of prepared leaf dipped in silver nanowires.

an off-the-shelf copper coil that I connect to the heating elements with the non-toxic silver ink.

At this point, the packaging is functional, but there is no visual feedback or other interactive feature to suggest to a user when the packaging is hot. For this, thermochromic elements can be added to the outside of the packaging as an indicator of "readiness," as seen in Figure 3.8. I mix thermochromic pigment with a non-toxic, water-based glue and brush it onto one face of the packaging in a decorative pattern. The thermochromic design may alternatively be applied via screen-printing.

To create a heat-activated resealing mechanism, beeswax is melted and stirred with damar resin and jojoba oil (beeswax:resin:oil volume ratio of 4:1:1) in a double boiler for 15 minutes. Once all components are combined, the mixture is brushed as a strip onto 2 sides of the inside of the packaging and air-dried for 1 minute. This allows the packaging's contents to stay fresh and helps prevent any small pieces from falling out.

The assembled packaging is shown in Figure 3.9. The fabrication process described is done by hand, but several steps can easily be adapted to computer-aided or automated manufacturing processes. For example, conductive ink may be selectively deposited via well-established ink-jet or screen printing processes for higher throughput and higher precision assembly.

Figure 3.7: Left: Open-faced view of the leaves, silver traces, and paper packaging. Right: Reverse side of packaging showing charging coil (off-the-shelf copper coil used as stand-in for printed silver coil).

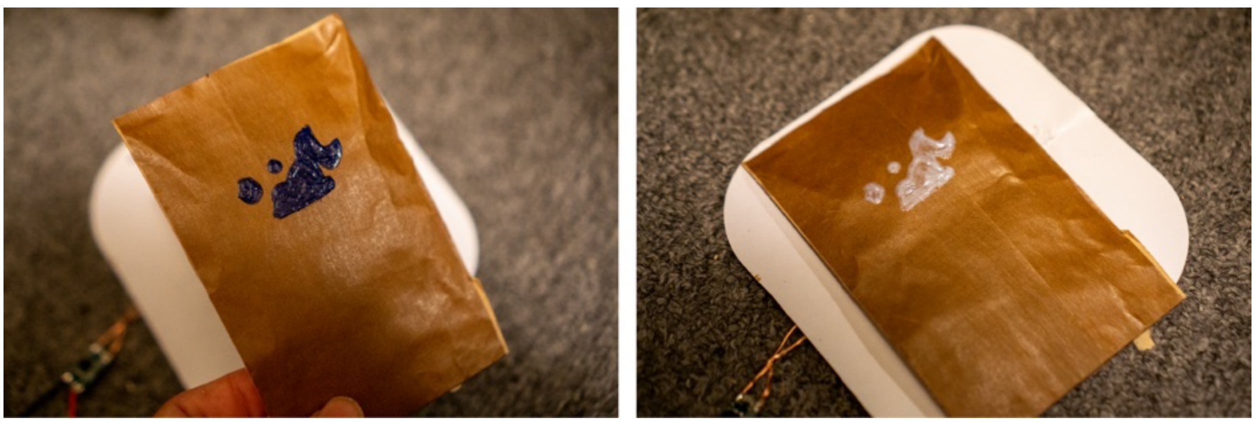


Figure 3.8: Thermochromic inks are used to indicate when the packaging is hot. Left: thermochromic ink design is purple before the packaging is heated. Right: Thermochromic ink design turns clear when the packaging is placed on a wireless charger.

3.5 Evaluation

3.5.1 Electrical and Heating Characteristics

The wireless charger used in this study has a DC input voltage range of 5-12V that I varied with a DC power supply to better characterize the electrical and heating characteristics of the packaging. A plot of the current consumed by the charger (with the packaging placed directly on the charging mat) vs. input voltage is shown in Figure 3.10. As seen, the relationship is linear, indicating a constant resistance across the range of operation. By taking the inverse of the slope of the least squares regression line, I calculate the effective resistance to be 15.5Ω. This was also confirmed via direct measurement with a standard

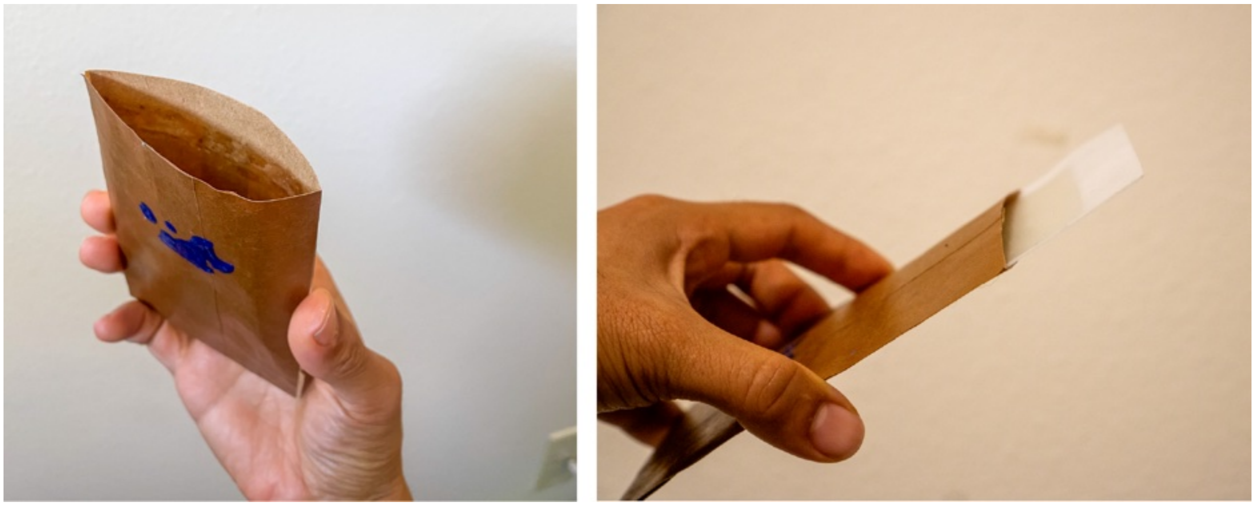


Figure 3.9: Images of fully assembled packaging with integrated leaf heaters.

multimeter.

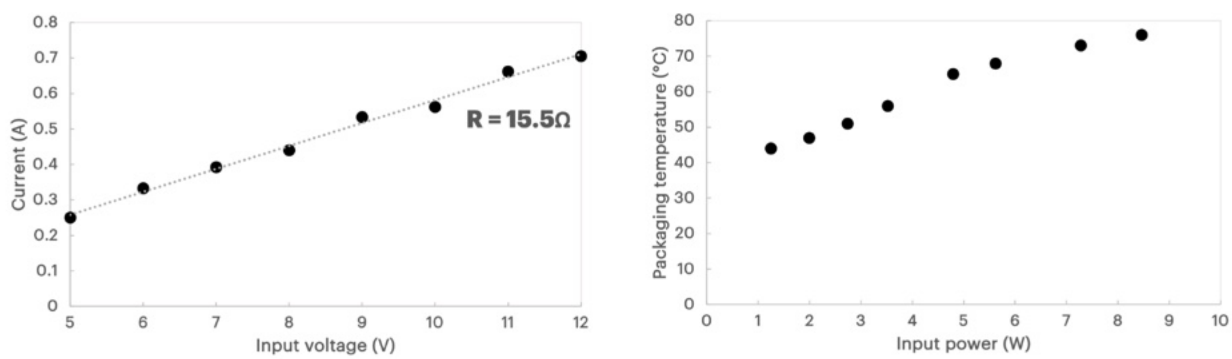


Figure 3.10: Top: Measured charger current vs. input voltage with the packaging placed directly on the charging mat. Bottom: Packaging temperature vs. charger power consumption.

Figure 3.10 also shows the relationship between packaging temperature and charger power consumption. I used an FLIR C2 Compact Thermal Imager to monitor the heating of the packaging. Ambient temperature was 23°C for the duration of the test. At each voltage step, the temperature was monitored for and recorded after 20 seconds. The temperature stabilized within a few seconds and remained constant during the 20 second period. Even at a low power of 1.25W (corresponding to 5V and 250mA), the packaging was able to heat to 44°C, or 21°C greater than ambient temperature. As expected, temperature increased roughly linearly with power, up to 74°C at a power of 8.46W (corresponding to 12V and 705mA). As a point of comparison, a standard incandescent light bulb consumes 60W, and an equivalent-lumens LED light bulb consumes 12W [293].

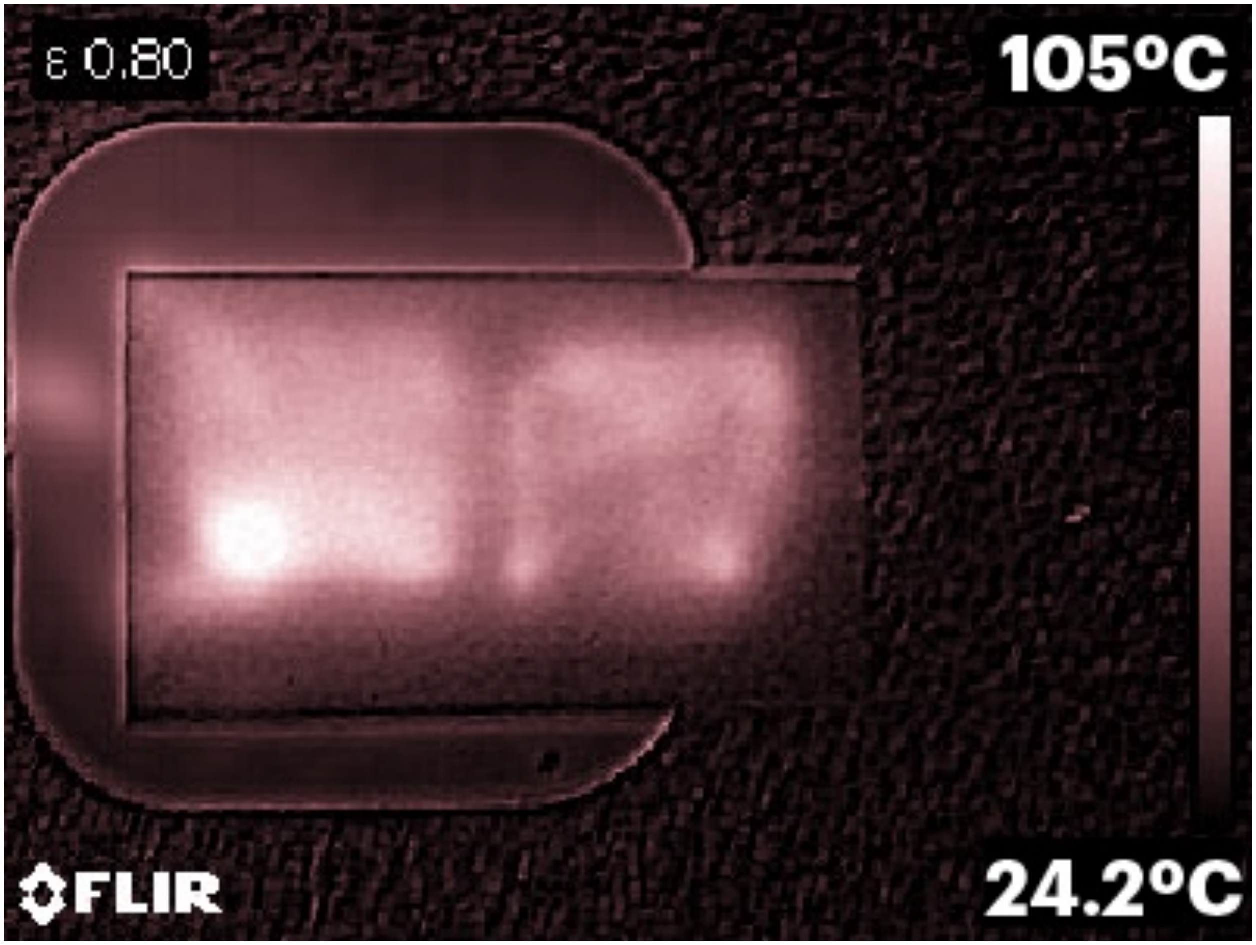


Figure 3.11: Infrared image of package placed onto charging mat.

An example IR image of the package taken seconds after being placed on the charging mat (input voltage = 12V) is shown in Figure 3.11. Uniformity across the sample is analyzed with ImageJ[2]. The average temperature across the two heating patches in the image in Figure 3.11 is 73.6°C +/- 11.3°C.

The temperature and power consumption of the packaging is stable over long periods time as well. I left the package on the charging mat for 8 hours and observed no change in average temperature or power, as measured by the power supply to the wireless charging mat. I also conducted a cycling test in which I moved the package on and off the charging mat in 5 minute on/5 minute off cycles and similarly observed that the temperature and power remained the same for 20+ cycles.

[2] https://imagej.nih.gov/ij/

3.5.2 Degradation

Figure 3.12: Left: packaging before being buried in soil on day 1. Middle: packaging dug up after 15 days. Right: packaging dug up after 30 days.

I created a swatch containing all components of the packaging — paper tape, NW-coated chitosan-leaves, silver ink, beeswax sealing, and thermochromic ink — and buried it under 20 cm of soil in a community garden in Berkeley, California for 60 days. The soil was alluvial soil with a moisture content of 30% as measured by a handheld moisture meter. The packaging was dug up and photographed on day 15 and on day 30 as intermediate checkpoints. The test was conducted during the summer of 2021. The swatch very visibly decomposed over the course of this test, as seen in Figure 3.12. After 60 days, the swatch was again checked on, and it was visually indistinguishable from the surrounding soil. This is unsurprising, since I intentionally selected components that are known to be backyard-degradable. Known decomposition times of each components are reported in Table 3.1. Decomposition times do vary across different environments, but one can readily see that the time scale for decomposition is orders of magnitude smaller than the hundreds of years that even plastics marketed as "eco-friendly," such as PLA, take to naturally degrade.

3.6 Applications for Leaf Heaters

I next discuss several applications for the leaf heater system, both as packaging and as a platform for other designs.

Table 3.1: Component Decomposition Times in Soil

Component	Decomposition Time
Leaves	21-365+ days [115]
Chitosan	30-60 days [244]
Paper	28 days [271]
Beeswax	14-28 days [110]
Thermochromic ink	50-180 days [348]
Ag NWs	<1 day in water [394]

3.6.1 Food

Food is a basic necessity for all as well as a subject of delight for many. Access to health-safe food is limited by the regional availability of processing, packaging, and storage technology. Pasteurization is one important but simple technique relied on worldwide that uses mild heat to destroy harmful microbes in liquid foods without changing the nutritional content or taste. This process is critical for treating products such as milk and juices. The pasteurization of milk requires a sustained temperature of 63°C for 15 minutes or 72°C for 15 seconds to sufficient to destroy all yeasts, molds, and gram-negative bacteria [140]. These parameters are easily achievable by the leaf heaters, positioning them as an attractive solution for food safety in environments and locales where specialized equipment is unavailable.

The packaging may also be used as a reusable receptacle for heating food for more optimal enjoyment. To demonstrate this, I took a store-bought chocolate chip cookie, placed it in the packaging, and placed the packaging on the wireless charger (input voltage = 12V) for 2 minutes. After removing it from the packaging, the cookie was soft, and the chocolate chunks had been melted (Figure 3.13). Similar scenarios could be useful for other snacks or beverages in various settings, such as outdoors on a hike or in an airport, where microwaves and other kitchen appliances are not readily available, or in situations in which it might not be desirable to share such equipment. With a few basic modifications, instead of taking the shape of a rectangular bag, the packaging could be a sheet with pre-creased origami folds (or pre-scored kirigami cuts) so that it may be transported and stored flat but be easily assembled into aesthetically interesting and/or functional 3D shapes, such as bowls for soup.

3.6.2 Activating Shape Changes

4D printing and shape-morphing materials are active research areas that promise to revolutionize many fields, such as manufacturing, shipping, implantable devices, and tangible user interfaces [187, 327]. Many of the popular approaches rely on heat to activate a programmed-in shape change [354, 353, 9, 106, 100]. As proof-of-concept demonstrations, in research papers, the changes are usually activated with a radiative heating lamp, hot water, or a commercial Joule heater wired to a power source. Small, lightweight, and eco-friendly

Figure 3.13: Cookie before (left) and after (right) being heated in the packaging for 2 minutes.

heaters such as the one of this chapter could be used to make such demonstrations portable, perhaps opening the door for more applications.

Shape-changing elements could be also integrated into a packaging form factor to indicate prior usage, perhaps as a safety feature or perhaps as a decoration. For instance, Gu et al. demonstrated that by varying print speed and direction, a 3D printer may be used to print objects that lie flat when printed but morph into 3D forms as specified by the designer when later heated [106]. These objects could be adhered to the outside of packaging, with a shape changing indicating if the package has been heated before. This could help a user determine if the packaging's inner contents are safe or valid. Depending on aesthetic preferences, these features could be designed to be spartan and purely functional, or they may be intentionally designed to be playful and whimsical.

Heat-activated shape-changing materials such as expanding foams, made from silicone and thermally-expanding microspheres [142], can also be incorporated into the packaging to protect arbitrarily-shaped contents. The unexpanded foam can be packed flat into the walls of the packaging to allow for easy transport when the packaging is empty. Once the packaging is filled, the expanding foam can be easily activated to inflate and conform to the contents by placing the packaging on a charging mat. An example of packaging filled with thermally-expanding microspheres before and after heating is shown in Figure 7.4.

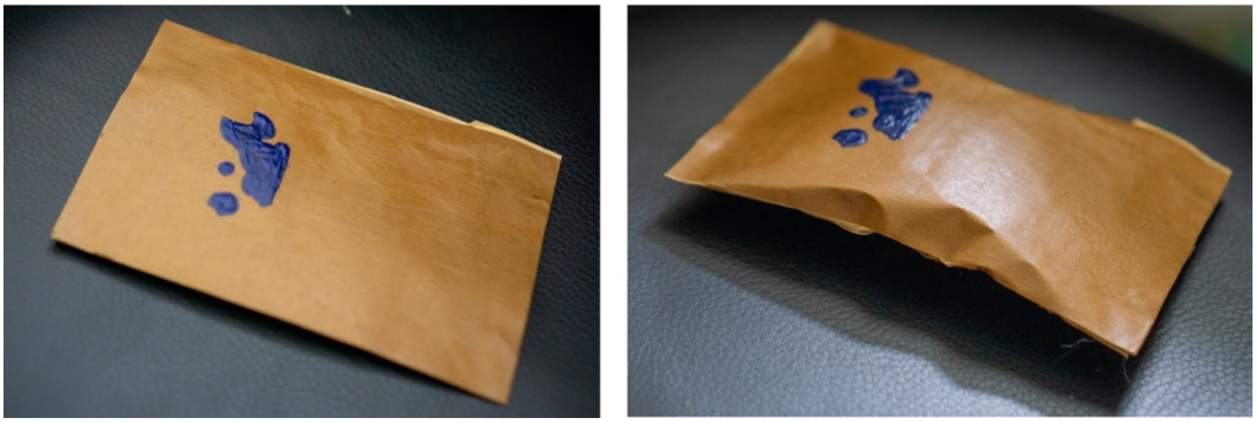


Figure 3.14: Thermally expanding microspheres placed inside the packaging can be activated to provide padding or achieve a desired shape.

3.6.3 Enhancing On-Body Experiences

There are several cosmetic and personal health products that the packaging can also enable and improve the experience of using. For instance, waxing strips must be warmed before they are able to adhere to skin. I placed such a strip inside the packaging, and after just a few seconds, the product was ready for use (Figure 3.15). Other items that need to be heated for an optimal user experience include lotions and essential oils.

Beyond being integrated into packaging for such on-body products, the leaf heater system could be applied as semi-permanent on-body wearables. One straightforward implementation is as a stand-alone heat therapy patch. The system may also be used to activate thermoresponsive designs on clothing. Additionally, there are several reports of interactive wearable designs that require heat to activate, but like the shape-changing interfaces previously discussed, demonstrations are conventionally done with a non-portable or otherwise bulky power scheme. They are either wired directly to an external power supply or battery, which drives current through the wearable, or heated with conventional Joule heaters that are in turn wired to an external power supply or battery. Kao et al.'s *SkinMorph* is a hydrogel-based wearable that can programmably change texture based on temperature [148]. In Kao's presentation, Nichrome wires are sewn into SkinMorph patches and wired to a battery-powered circuit board. The leaf heater system could potentially simplify the use and eventual disposal of such a wearable.

Figure 3.15: A waxing strip becomes pliable and is able to stick to skin after being heated in the packaging for a few seconds.

3.7 Discussion and Future Work

3.7.1 Leveraging Wireless Charging

This design takes advantage of the growing ubiquity of wireless charging systems. Such inductive charging hardware is increasingly available and used to charge mobile phones, smartwatches, headphones, speakers, and more [267, 216]. This enables us to exploit a growing ecosystem of power to drive the novel heater design. By decoupling the power from electronics and the heater design, we are able to create a truly backyard-degradable, interactive system. We are also seeing a rise in the number of mobile phones and other IoT devices that are capable of bi-directional charging — that is, mobile phones that can receive charge wirelessly as well as deliver wireless charge from their internal battery. For example, Samsung's Galaxy S10 is able to provide 4W of power wirelessly [331] to other devices. This level of power would allow the backyard-degradable heating design to easily operate on the inductive coupling from a mobile phone alone and heat to 60°C, which is more than sufficient for most applications. This also significantly increases the ease of operation, variety of interaction, and range of functional places, since the heater can simply be triggered by placing it adjacent to a mobile phone, which is easily and commonly carried and thus readily on hand. Looking into the future, there is also budding research on fully biodegradable batteries [172, 59] that could eventually enable even more applications of backyard-degradable interfaces in environments where wireless power might not be a feasible option.

3.7.2 Beyond Heaters

I envision how a focus of constraining designs to use only backyard-degradable materials can also be extended beyond the heater example discussed in this chapter. For instance, as mentioned in the related work section, the branching fractal structure of the leaf skeletons is also promising for pressure sensing. We could apply a very similar design approach to what I present here to create a fully backyard-degradable wirelessly-powered system for this application.

Even more possibilities for backyard-degradable designs may be imagined when I broaden out from the exact materials I use in this chapter. Beyond smart packaging, many other applications are also well suited for backyard-degradable electronic design. As an example, in spite of a growing counter-movement to fast fashion, consumers generally do not keep an item of clothing or accessory until its end of life, instead often letting go of pieces that no longer suit their ever-changing style. While there is an argument to be made for making durable, smart garments that can change color, texture, and style electronically to keep up with trends, research suggests that smart, especially wearable, devices are often abandoned after a short period of use [99, 181]. Instead of building entire electronic systems into clothing that complicate end-of-life handling, we can employ the same power decoupling strategy of my design – for example, a non-backyard-degradable mobile phone with bi-directional charging could be leveraged to wirelessly power and illuminate fully backyard-degradable, electroluminescent patches sewn into or adhered to the clothing fabric. Similarly, sensor networks or other equipment deployed to a remote or dangerous environment could have limited operating lifetimes that allow useful data to be collected without the need to retrieve or remove the sensors, since they would degrade into non-toxic components soon after use. Of course, while significant scientific advances are still needed to realize all of these systems, I have clearly demonstrated a first step. My argument is only that through the novel usage of selected backyard-degradable materials, limited but useful electronic technologies can be designed and put into operation. Such systems will have limitations, such as intermittent power, slow operation, short duty cycles, and limited storage. Indeed, as more explorations are done in this area, we inevitably will find that certain applications do require long-lasting, speedy electronics that are difficult to achieve with backyard-degradable materials. However, I believe that there is still a range of other applications for which these trade-offs are more than worth it for the tremendous benefits that come with a backyard-degradable system.

3.7.3 Aesthetics of Backyard-Degradable Electronics

Here, I chose to sandwich leaf heaters between two paper layers to create packaging that takes on the appearance of a standard paper envelope. This approach of prioritizing aesthetic *typicality* might be advantageous for promoting the adoption of leaf-based heating systems among people who are wary of the unknown or unfamiliar [152]. Alternatively, the leaves could intentionally be exposed by encapsulating them with clear, degradable cellophane tape instead of paper tape, or they could be left un-encapsulated entirely to fully showcase their appearance and texture. Leaf-based heating systems could thus become a vehicle to express personal style, perhaps as a pairing with gold or silver-dipped leaf jewelry. Furthermore, since no two leaves are identical, each system would have a unique, one-of-a-kind appearance that could increase one's emotional attachment to the system and also consequently promote more sustainable reuse practices [39].

Even after end-of-life is inevitably reached at some point, there are more opportunities to take advantage of the unique aesthetics of backyard-degradable electronics. Because backyard-degradable systems are degradable in one's own backyard, they may give rise to new enriching experiences even after they are no longer able or wanted to be used for their original purpose. By selecting materials that degrade at different rates — for instance, in Figure 3.12, the beeswax strip appears to degrade slower than the paper, silver, and leaf components — a designer may intentionally exploit those differing decay rates directly into their design. This incorporation of *unmaking* [304] into objects is a critical new formulation in how designers design. That is, designers design not only for form and function but also for the range of intermediary forms and sub-functions of a digital artifact as it progresses towards its eventual decay. This fluid design could also celebrate and capture a broad range of ephemeral [315] transitory designs. Similarly, Liu et al. describe the degradation of natural materials as an opportunity for "natureculture co-creation" — a collaborative design process between nature and humans that de-centers the role of the human designer, encouraging humans to connect with nature [201]. As a backyard-degradable interface changes form or texture, it could hence inspire a more intimate connection to the material object and decay experience [23] in addition to provoking reflections around the environment, consumerism, craftmanship, and materialism [201].

3.7.4 Challenges and Future Work

The design I have presented is Do-It-Yourself (DIY)-friendly in that it relies entirely on off-the-shelf, non-toxic materials and household-safe equipment and processes to make. As mentioned, I use a proxy copper coil in the demonstration here in place of a printed Ag NW coil, for which the capability and process of printing such a coil is well documented [274, 190, 85, 396]. However, printing an Ag NW coil does require a conductive ink-jet printer and electromagnetic simulation software to optimize the coil geometry for efficient power transfer. Next steps will be geared towards replacing the proxy coil with a printed one to eliminate the need for coil detachment before composting. With further material exploration, it may be possible to build even more sustainable systems than what I demonstrate here. One future avenue of research lies in exploring the possibility of harvesting the heat released from fermentation or other organic processes. This could pave the way for completely stand-alone heating systems that are self-powered without relying on any non-natural power sources — wired or wireless — at all.

Even though I believe that a person without specialized design, materials science, or engineering experience can successfully acquire the materials and follow the fabrication process presented in this chapter, I acknowledge that using unfamiliar materials can be intimidating. As such, I have made available a single-page manual with links to purchase materials and step-by-step instructions. I envision that such instructions could be distributed in a self-contained kit with pre-portioned quantities of all materials needed to make a desired number of heaters, further facilitating DIY fabrication and exploration and allowing this design to be more widely adopted. More broadly speaking, when it comes to exploring new materials and other designs, I acknowledge the difficulty of weeding through years of research in biology and materials science to find natural, degradable materials that might be suitable. Sometimes, even understanding what materials are "safe" and/or biodegradable can be a challenge. To facilitate this, building an open-source library of natural materials, such those compiled in the online recipe database *materiom*[275], could help facilitate the selection and subsequent design of a wider range of backyard-degradable smart systems. Suggestions for what materials to use could even be directly integrated into conventional design tools, such as CAD modeling software, to further assist designers form more sustainable creations.

I believe that DIY-friendly materials and designs are critical to inspiring new uses of sustainable materials and are also useful in enabling unique aesthetics even among different artifacts that arise from the same set of instructions. Still, I understand the value of enabling the eventual large-scale production of sustainable designs, which perhaps start as DIY approaches, to maximize awareness and use beyond what might be enabled even by the aforementioned self-contained kits. For the design presented in this chapter, more experimentation is needed to understand if larger designs could be created by using larger leaves or by layering multiple leaves together with chitosan or another backyard-degradable binder. In general, one challenge of using natural materials is that they are often inherently non-uniform. For example, leaves may have natural holes or areas of sparse venation that could affect their efficacy as heaters on large scales. To address this, one possible approach is to simply take inspiration from the branching structure of leaf veins to design large-area networks of artificial skeleton leaves made from an alternative backyard-degradable material that can be 3D-printed, milled, or otherwise digitally fabricated into the desired form.

3.8 Conclusion

I have presented the design of a backyard-degradable, wirelessly-powered, and portable heating system that is integrated into packaging. I argue that by prioritizing the use of natural and backyard-degradable materials early in the design process and considering how we can leverage existing wireless energy transfer technologies, we can create functional, interactive interfaces with materials that are already commercially available. I have detailed a space of applications for temporary, low power interactive systems, such as the packaging I presented, for which I believe backyard-degradable materials are particularly well suited. I further encourage designers to leverage a materials-first product design process that prioritizes the use of biological structures and natural materials to create additional novel applications and designs that are backyard-degradable.

Chapter 4

Füpop: Wireless In-Mouth Flavor Experiences

In the previous chapter, I presented thin film heaters based on leaf skeletons that could be wirelessly activated by inductive chargers for electronics. In this chapter, I leverage a similar technique to explore how *food* can be an interactive material for backyard-degradable electronics [1]. I create a novel system for human-food interaction whereby one component is entirely backyard-degradable – specifically, edible – and the other components is a reusable focused ultrasound transducer that can be integrated into existing electronics and used to wirelessly activate the backyard-degradable component. I show how this approach opens up new possibilities for in-mouth technologies for human-food interaction (HFI), a subfield of HCI that was first written about in the 1990s and has exponentially increased as the topic of publications since the early 2000s [6]. By leveraging wireless energy transmission and separating the degradable (edible) and non-degradable components, I achieve a system that, unlike existing taste interfaces, does not require the mouth to remain open for wires or tubes for external electronics or chemicals.

Despite the importance of food and flavors to our existence in the world, taste remains an under-explored sense in interaction design. I present Füpop, a technical platform for delivering in-mouth flavors that leverages advances in electronics and molecular gastronomy. Füpop comprises a fully edible pouch placed inside the mouth against a cheek that programmatically releases different flavors when wirelessly triggered by a focused ultrasound transducer from outside the cheek. Füpop does not interfere with activities such as chewing and drinking, and its electronics may be integrated into devices already used near the cheek, such as mobile phones, audio headphones, and head-mounted displays. Füpop's flavors are from "real foods," not ones imitated with synthetic reagents, providing authentic, nutritive flavors. I envision that with Füpop, flavors may be synced to music, a phone call, or events in virtual reality to enhance a user's experience of their food and the world.

[1] Large portions of this chapter have previously appeared in the 2024 ACM CHI proceedings. The original citation is as follows. Katherine W Song, Szu Ting Tung, Alexis Kim, and Eric Paulos. 2024. Füpop: "Real Food" Flavor Delivery via Focused Ultrasound. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 360, 1–14 [305].

4.1 Introduction

Food is inherently easily degradable – sometimes in a backyard but more frequently in the human body. Food is not only a necessary component for our survival but also a centerpiece of personal, social, and cultural experiences [112, 235]. Accordingly, human-food interaction (HFI) has garnered great interest within the Human-Computer Interaction (HCI) community. HFI has been the subject of a Special Interest Group at CHI 2022 [62], as well as multiple workshops [75] at CHI [74, 63], CHI PLAY [46], and DIS [73, 58]. Recent demonstrations of HFI technologies have spanned the integration of digital fabrication techniques into food preparation processes [158, 234, 92, 195, 170, 383, 233], the alteration of eating experiences through the stimulation of non-taste senses [32, 245, 359, 358, 344], and the creation of lickable "taste displays" that synthesize different flavors [231, 232]. Still, there are opportunities within HFI that remain under-explored. In particular, there is a dearth of technologies that enable dynamic interactions with the sense of taste after food leaves the plate and enters the mouth, with most demonstrations to date instead focusing either on the state of food before it enters the mouth or on the manipulation of senses other than taste to create illusory experiences. We still largely lack the means to manipulate, in real time, taste and texture in the mouth, one of our most important and densely innervated organs [107, 52] that is rife with opportunities for interactive technologies.

Interestingly, the few systems that do manipulate taste via direct interaction with the tongue and mouth [231, 232, 277, 276, 278, 254, 30] often do so without using items commonly considered to be food, instead using materials and techniques that do not provide a nutritive or caloric benefit to the user. This is in part by design, but it is also in part due to the fact that research in functional, edible materials and electronics is still in its infancy [108, 382, 298]. Nonetheless, I believe that prioritizing the use of "real foods"[2] over synthesized flavors is a promising direction to create authentic taste experiences that are not inherently limited by the drawbacks of imitation. Despite the wealth of recipes and techniques that chefs have perfected to serve up plates of food with delightful aromas, flavors, and textures, interaction designers have limited means to utilize "real foods" for in-mouth interactions and interfaces. Additionally, exploring edible ingredients and in-mouth interactions provides a unique opportunity to expand the space of sustainable and backyard-degradable interactive electronics. Edible materials are by definition easily degradable, generally possessing far lower carbon footprints than plastic alternatives or conventional electronics [330], and they are ideal candidates for designing unmaking experiences [304] or ephemeral user interfaces [316].

Illustrated in Figure 4.1, in this chapter, I present Füpop, a technical platform that enables programmable, dynamic in-mouth flavor experiences with real food. The name

[2] I use the term "real food" in this chapter to encompass not only whole, natural foods but also processed foods and ingredients that are commonly consumed on their own or used in widespread cooking methods such as baking. These are distinguished from chemicals sometimes used for artificial flavoring that are merely "safe" and/or "non-toxic."

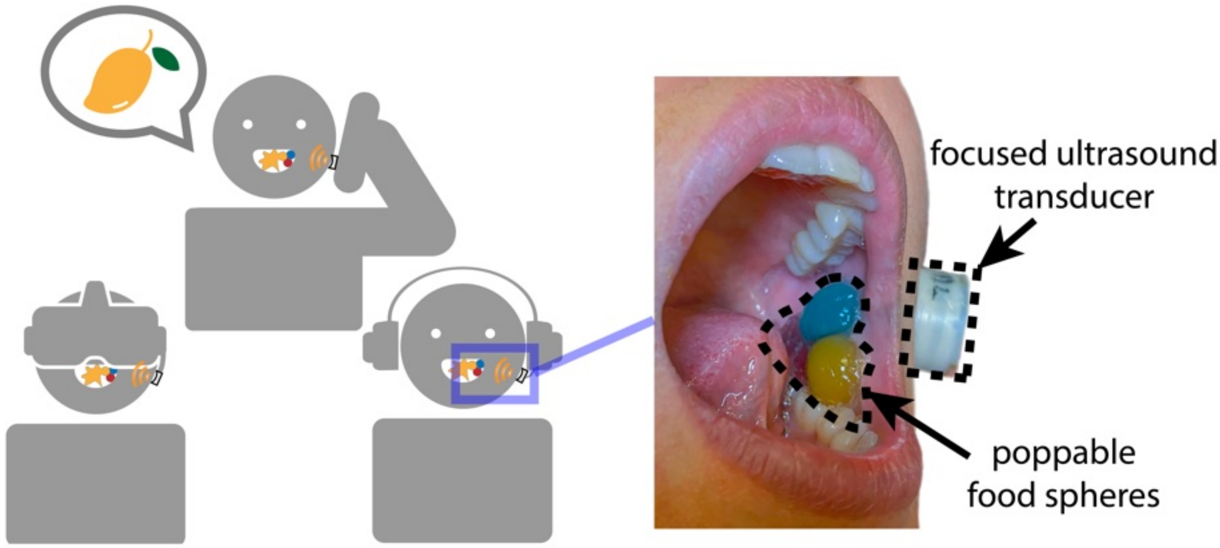


Figure 4.1: Left: Schematic showing an envisioned interaction with Füpop whereby three individuals communicating in real time via phone (using a cell phone, head-mounted display, and/or headset) may experience choreographed flavor experiences synced to the content of a call, e.g. tasting mango juice as one individual describes their memorable mango-eating experience. Right: Füpop comprises (1) a small focused ultrasound transducer placed outside the cheek that can be integrated into cell phones, audio headphones, or head-mounted displays; and (2) a 100% edible pouch, placed inside the cheek, that encloses calcium alginate spheres filled with different liquid foods.

Füpop comes from the common shorthand "FU" for "focused ultrasound" combined with "pop" to represent the popping nature of the spheres in the edible portion of the system. I aim to utilize edible materials as much as possible and minimize the footprint of any non-degradable electronics, similar to the strategy I used in the previous chapter. To do this, I relegate active electronic components to be completely outside the mouth – with the vision that they may be integrated into wearables or electronics already used on and around the face – and create a module existing entirely in the mouth with fully edible ingredients that are selectively responsive to external stimulation. In particular, I leverage the abilities of ultrasound energy to be transmitted wirelessly and to mechanically excite structures through the skin. Füpop comprises a completely edible pouch enclosing multiple different flavor capsules that unobtrusively rests inside the mouth against the cheek. The pouch does not readily dissolve or melt on its own in the mouth. I envision that future food designers may use Füpop to choreograph a taste experience for the eater whereby different flavors are sequentially released into the mouth and synced to different electronic stimuli, enabling more immersive musical or virtual reality experiences and allowing for novel interactions and communication, such as "taste messages," that individuals may send to one another.

Füpop combines innovations in non-edible electronics along with those in molecular gastronomy and culinary science to create programmable flavor sequences with real, edible, and potentially nutritious ingredients that are not illusory or synthetic. Füpop does not require that a user's mouth remain in a fixed position and does not interfere with normal mouth activities such as chewing, drinking, swallowing, or talking. With low-profile electronics existing outside the face, dynamic experiences can be computationally triggered in real-time in response to stimuli such as music, gaming events, or bio-signals. In the subsequent sections, I present the following contributions:

1. The design and fabrication of Füpop
2. Ex vivo characterizations of design parameters that can be used to customize different flavor sequences, along with preliminary in vivo qualitative experiences
3. An ex vivo demonstration of a multi-flavor Füpop
4. Discussion around the applications, future embodiments, and significance of Füpop.

4.2 Related Work

Füpop draws inspiration from a rich body of research in HFI and ultrasound technologies. To this point I have presented much work in the domain of degradable materials and systems; this chapter explores how *food* can be such a material. Here, I summarize prior work in HFI and ultrasound specifically and describe how this chapter is situated with respect to existing approaches.

4.2.1 Human-Food Interaction

HFI spans a huge range of research that investigates the interplay between humans and food in nearly every aspect of our lives. Bertran et al. categorize HFI research into 6 domains: "Source" (obtaining food), "Store" (storing and disposing food), "Produce" (growing and manipulating food), "Track" (measurement of practices around food), "Eat" (consuming food), and "Speculate" (design fictions, meta-analyses, etc.) [7]. Here, I present existing work in the "Produce" and "Eat" domains, focusing in particular on technologies that create new textures, aesthetics, and flavors during the food preparation and eating processes.

In the "Produce" domain, there have been numerous demonstrations of methods for crafting unique food textures and aesthetics, often integrating digital fabrication machinery, such as laser cutters and 3D printers [158, 234, 92, 195, 170, 383, 233], novel mechanical contraptions [399], or displays and other electronics [131] into the food preparation and serving experiences. Some of these technologies have been used to concoct dishes and flavors that reflect non-eating activities like physical exercise [159, 158], while others have been used to investigate the relationship between taste and emotion both personally [94] and in intimate relationships [93]. Some engineered characteristics during production also affect the subsequent eating experience. For example, FoodFab is a 3D printing system that allows a user to modulate infill pattern and density, in turn influencing an eater's chewing time and feeling of satiety [195]. Shape-changing edible materials have also been developed and proposed as ingredients that enhance chefs' food preparation experiences and also open up possibilities for novel dining interactions [337, 76]. Researchers have indeed begun to design provocative systems that encourage and change the way diners can interact with and influence the qualities of their food before it comes to the plate. Logic Bonbon is a system in which users may squeeze flavored liquids into a bonbon that has internal fluidic chambers embodying digital logic gates. The combination of users' interactions with the bonbon and the bonbon's internal structure determines its resulting flavor [61].

In the "Eat" domain of HFI, technological approaches have largely focused on developing non-edible electronics, existing at least partially outside the mouth, that augment or simulate the experience of eating. One popular strategy to influence the taste of a food is to create multi-sensory experiences with other senses, particularly visual, audio, and tactile stimuli [246, 32, 245, 344]. Some systems employing this approach take the form factor of functional utensils that can interface directly with food. For example, Wang et al. presented ice cream cones [359] and drinking straws [358] that enhance users' eating and drinking experiences with sound to encourage playfulness and social intimacy.

While far less common, there have indeed been a few demonstrations of systems that manipulate the sense of taste itself, creating dynamic flavor interactions on the tongue. One method for this is to directly stimulate the tongue with electrical current. The tongue can readily perceive microamps of current, with reported thresholds as low as 5µA [313]. Ranasinghe et al. presented an array of utensils and devices, such as a "Digital Flavor Synthesizer," that, in conjunction with heating and cooling elements, use 20-180µA of current to simulate sour, spicy, and minty tastes [277, 276, 278]. Another approach that Miyashita pioneered is to simulate different flavors with lickable electrophoretic "taste displays" comprising a set of agar gels with various electrolytes that mimic 5 basis flavors (salty, acidic, bitter, umami, and sweet). Miyashita recreated certain tastes, as measured with an electronic taste sensor, by modulating the electric potential across each gel and thus the concentration of electrolytes at the surface of the tongue [231, 232]. Miyashita's Norimaki Synthesizer is a taste display in the form of a handheld stick that, while not designed to be eaten, is safe to lick [231]. Finally, Brooks et al. presented a system for "taste retargeting" whereby liquid chemical modulators could be delivered into the mouth via tubes to alter the perceived taste of a certain food [30].

While greatly influenced by the above work, Füpop is fundamentally different in that it delivers flavors that can be experienced during the act of eating with real, edible, and nutritive foods that are not illusory or synthetic. Additionally, with low-profile, wireless electronics outside the mouth that can be integrated into existing electronics, Füpop does not require that a user's mouth remain open or closed or that special utensils are used, minimizing unnatural disruptions to normal eating and mouth-related practices.

4.2.2 Ultrasound in HCI

Füpop harnesses the power of ultrasound technology to induce in-mouth experiences from outside the mouth with no physical wires between the two domains. Ultrasound is electromagnetic energy existing at frequencies above 20kHz, the upper threshold of human hearing. It is conventionally generated by exciting piezoelectric elements with an alternating electrical signal, causing them to vibrate at the stimulation frequency. Ultrasound is perhaps best known for its applications in the medical space, but it has attracted great interest in the HCI community as well. In medicine, ultrasound is commonly used for imaging [83] and several different active therapies, including tissue healing for physical rehabilitation [324, 227], transdermal drug delivery [230, 227], and targeted tumor ablation [156, 230, 227]. It can be used non-invasively and is non-ionizing, unlike microwaves or x-rays, allowing it to be transmitted through healthy biological tissues with minimal risk [80].

In HCI, ultrasound has been instrumental in developing several novel interactive systems. UltraHaptics, reported in 2013, is one of the earliest of such systems; it comprises an array of 320 ultrasonic transducers that produce haptic sensations in mid-air [42]. Since then, many other systems based on arrays of ultrasonic transducers have been demonstrated to create mid-air haptics, especially on the hands [376, 251, 312, 221, 346]. This idea has also been used for haptic feedback on other body parts. Shen et al. demonstrated a system for generating haptic sensations in and around the mouth using an array of beamforming ultrasonic transducers attached to a virtual reality head-mounted display [299]. Other demonstrations have created haptic sensations on the face [96] and on the lips [137].

Within the HFI domain, ultrasound has been used to levitate, mix, and move edible droplets of liquid [345, 153]. Furthermore, ultrasound has been used to levitate other small objects [86, 89, 220], selectively deliver audible sounds to a targeted audience [252], create "digital ventriloquism" illusory effects whereby observers perceive passive physical objects to be active sources of audio [129], and sense gestures and facial expressions [130, 128]. It has even been utilized to wirelessly power electronics [236].

Ultrasound waves quickly attenuate when passing through heterogeneous media, including biological tissue, and thus their existence in HCI research to date has been primarily restricted to usage in obstacle-free settings – even Shen et al.'s mouth haptics system requires that the mouth be open for a user to feel effects on the teeth or tongue [299]. Researchers have reported a few techniques to overcome this challenge. SoundBender is a system that combines phased arrays of transducers and acoustic metamaterials to allow ultrasound beams to bend around small obstacles for mid-air levitation and haptic feedback [249]. Using arrays of phased transducers and time-reversal signal processing, SkinHaptics is another system that allows perceivable haptics sensations generated on one side of the hand to be felt on the other [310].

Instead of an array, Füpop utilizes a single high-intensity focused ultrasound (HIFU) transducer (purchased from AliExpress for $35USD). The transducer is functionally similar to those used in medical procedures to target malignant tumors beneath the skin without damaging surrounding tissue [156], but I operate it at much lower powers and for much shorter times. This simplifies the necessary driving electronics in comparison to phased arrays and also utilizes well established techniques for operating near and through the human body.

4.3 Füpop

Füpop is composed of 2 main components: (1) electronics existing entirely outside the mouth and (2) an edible pouch, made with Do It Yourself (DIY) friendly methods, existing entirely inside the mouth between the cheek and teeth. The pouch contains spheres of different liquid foods of the designer's choice that release their unique flavors sequentially when wirelessly triggered by the external electronics. In this section, I discuss the design and fabrication of each component.

4.3.1 External Electronics

A HIFU transducer with a resonant frequency of 4MHz, purchased from alibaba.com for $10 USD (Longzhichuang Co., Ltd.), is the core of Füpop's external electronics. The transducer is a cylinder 22mm in diameter and 10mm in height with a hemispherical piezoelectric ceramic element. Operating well above the frequency range of human hearing, the transducer is not audible when activated. Figure 4.2 shows an image of Füpop's transducer alongside a cross-sectional schematic illustrating how ultrasonic energy is focused through the skin. The main distinguishing characteristic of a focused transducer versus a normal ultrasonic transducer is that the focused transducer's vibrating piezoelectric element is shaped such that it forms a concave disc instead of a flat one, acting like a lens to direct ultrasonic energy towards a point in front of the transducer instead of being distributed and attenuated in multiple directions. This results in a concentration of acoustical pressure that can exist tens of millimeters deep in a heterogeneous medium while maintaining a safe and relatively low power density at the surface of the medium. It can, as I will show, create enough force to mechanically excite and rupture liquid spheres placed at or near the focal region.

The architecture of the driving electronics that I use for testing is shown in Figure 6.8. In comparison to the phased arrays described previously in Section 4.2.2 (Related Work), Füpop's single HIFU transducer may be simply driven by electronics that can generate a sine wave at the transducer's resonant frequency with sufficient amplitude. This can in theory be accomplished with a fairly small electronics package comprising (1) a microcontroller, connected to various signals and sensors of interest (audio, on-body sensors, etc.), that provides a trigger signal to (2) a driving circuit programmed to output the desired amplitude and frequency to activate the HIFU transducer. This package can be handily integrated into wearables and electronics that are already commonly used on or around the face, such as mobile phones, headphones, head-mounted displays, or face masks. For testing, however, I use a benchtop arbitrary waveform generator (SeeSii DDS-15MHz) amplified by a fixed-gain 55dB amplifier (E&I A150) to drive our transducer. The waveform generator

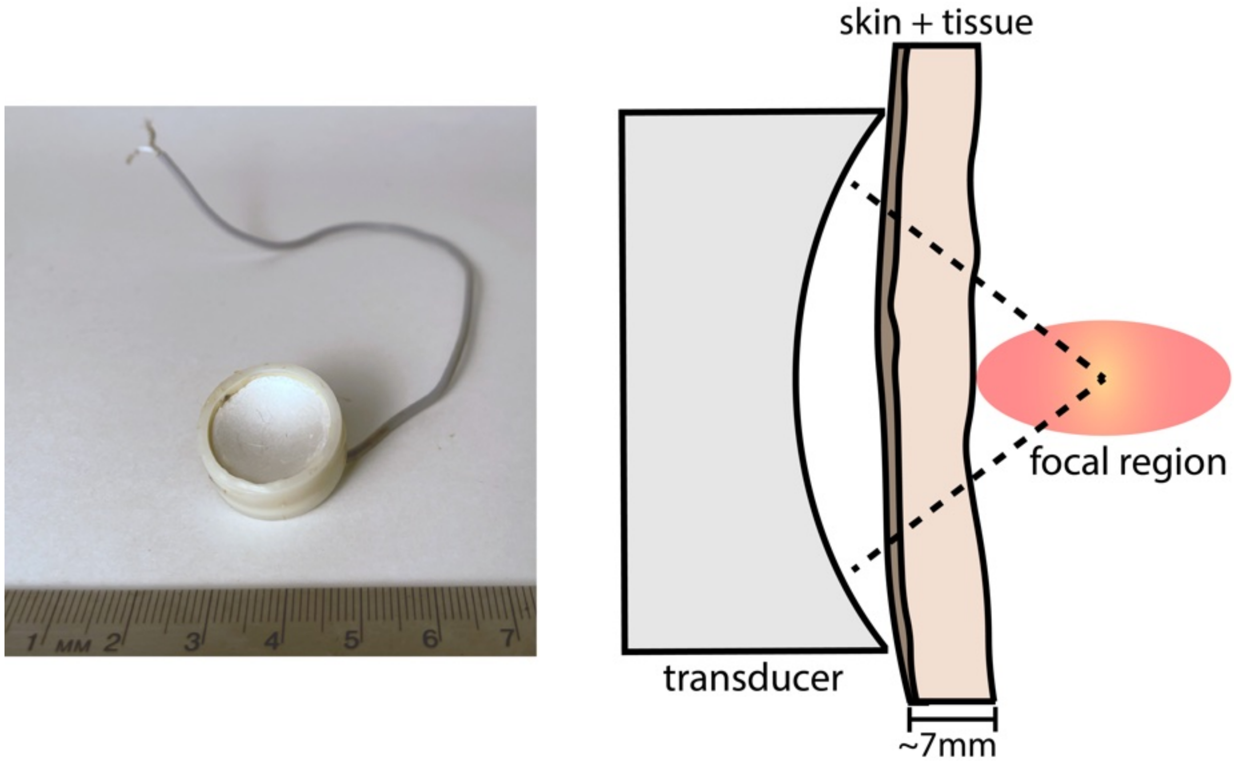


Figure 4.2: Left: Image of Füpop's focused ultrasonic transducer. Right: Cross-sectional schematic showing ultrasonic energy being focused at a point on the other side of the skin.

is set to output a sine wave with a frequency of 4.3MHz, which I empirically found using a frequency scan to be the point of lowest impedance and thus most efficient power delivery. All input and outputs are impedance-matched to 50Ω. An Arduino provides a 5V signal to the waveform generator to trigger an excitation pulse of 0.25s. By adjusting the output level of the waveform generator, I deliver an excitation signal to the transducer of up to $80V_{P\text{-}P}$. This corresponds to a power of $24W/cm^2$ at the surface of the skin. These conditions appear to be well within the regime of safe operation in and around the body; for reference, HIFU in medical applications is typically used at $>1000W/cm^2$ for multiple seconds (even minutes and hours) at a time [227, 377].

4.3.2 Edible Cheek Pouch

The edible component of Füpop, shown in Figure 4.4, is a pouch that is contained entirely inside the mouth and placed against the same cheek where the transducer rests on the outside. The pouch, made from an edible, flexible material like potato starch film or rice paper, encloses multiple spheres containing liquid foods of the designer's choice. The spheres are fabricated via reverse spherification, a well known technique in molecular gastronomy

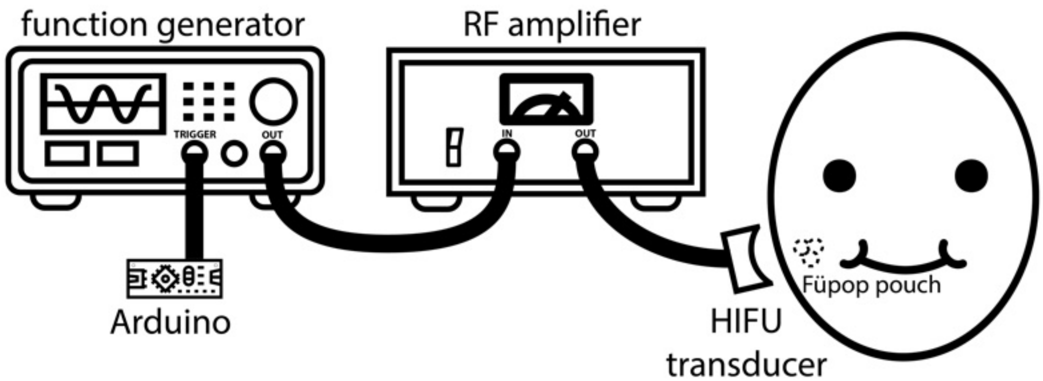


Figure 4.3: Füpop's HIFU transducer is driven by a 4.3MHz, 0.25s sine wave pulse. An Arduino provides the electronic trigger to activate a function generator, whose signal is amplified by an RF amplifier before being delivered to the transducer.

that results in delicate spheres of arbitrary liquids encased by a thin film of calcium alginate [255], which is an edible, tasteless material that is also frequently used in wound dressings [167]. Reverse spherification is used to make fruit caviar, "popping boba," and other culinary novelties. The process of reverse spherification utilizes completely edible ingredients and is safe and simple to make at home. The fabrication process is shown in Figure 5.4.

The method of making Füpop's edible pouch is straightforward, utilizing DIY friendly materials and methods. First, an alginate bath is prepared by mixing 0.5% (by weight) sodium alginate in distilled water at room temperature. Sodium alginate initially forms visible clumps that slowly dissolve over ∼30 minutes. Once the alginate bath is prepared, it may be stored in a sealed container and reused over multiple days. Next, 1% (by weight) calcium lactate is added to a flavored liquid, such as juice, milk, coffee, or soda. To improve the shape of the resulting spheres, up to 1% (by weight) guar gum, a tasteless food thickener, is added to increase the viscosity of the liquid to be the consistency of a thin syrup. Next, a pipette with a tip opening of 0.15 mm in diameter is used to drop the flavored mixture into the sodium alginate bath. The alginate in the bath reacts with the calcium in the drop to form a calcium alginate film around the drop. After 5-45 seconds, the resulting sphere is removed from the sodium alginate bath with a slotted spoon and placed into a clean water bath to halt the thickening of the calcium alginate film. Drops of 0.4-1mL are the easiest to handle. Larger drops tend to form misshapen spheres (though techniques, such as freezing the drops first, can mitigate this) and are hard to pack into a reasonably sized cheek pouch, and smaller drops hold less flavor and are therefore more difficult to taste when popped. The spheres may be stored in their constituent liquid for up to 1 week without a loss of texture or flavor. The calcium alginate films enclosing the spheres are thin but robust and are not soluble in water or alcohol. The spheres may be handled by hand and do not melt or

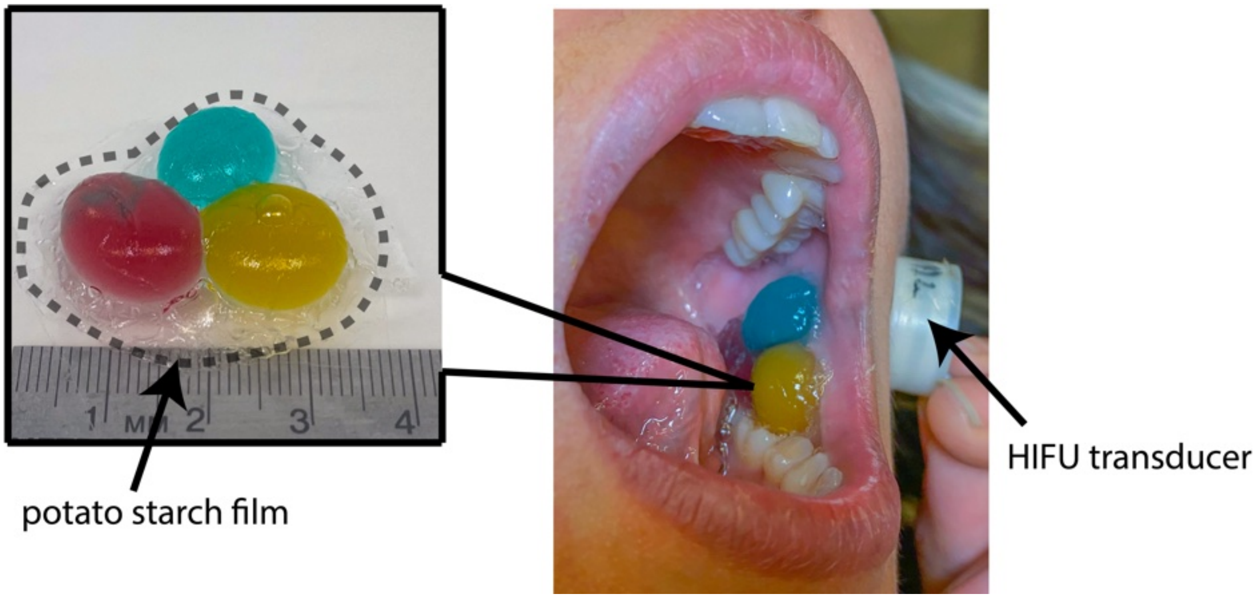


Figure 4.4: Füpop's edible cheek pouch encloses multiple spheres of flavored liquid (here, pink cranberry juice, yellow mango pulp, and blue sports drink). It does not readily melt or dissolve in the mouth. It is placed in the mouth between the teeth and cheek, where a HIFU transducer rests on the outside. Edible adhesives may be used to help keep the pouch in place against the cheek.

dissolve in the mouth. When a sphere is squeezed, the calcium alginate film pops, releasing the sphere's internal liquid (see Figure 4.6).

Multiple spheres are then packaged together using an edible material that does not readily dissolve in the mouth. Since the spheres themselves are resistant to saliva (remaining intact after soaking for >1 day), the wrapping films do not need to be impermeable to saliva, but they must stay intact in the mouth for a reasonable amount of time to hold the spheres in place. Meanwhile, the films must allow the inner liquid from burst spheres to escape into the mouth so that the user may taste them. I successfully made pouches with 0.28mm-thick grape leaves, 0.05mm-thick potato starch Oblate discs, which are digestible films for wrapping medicinal powders into a form to be swallowed, and 0.4mm-thick rice paper, which is commonly used to make the "summer rolls" of Vietnamese cuisine. I make 1mm-long perforations in the grape leaves and rice paper with a sharp knife to facilitate the release of liquid from popped spheres, but the Oblate discs are thin enough to render this step unnecessary. Both Oblate discs and rice paper are tasteless, self-adhering, and easy to cut and shape. They come in dried sheets, which I rehydrate in water, cut into pieces, and fold or roll into envelopes by hand to enclose the desired number of flavor spheres. Other wrapping options include perforated enteric-coated cellulose pill capsules, thinly sliced vegetables, or tea leaves. As I describe subsequently in our Characterization section, different wrapping films last for different amounts of time in the mouth, with some dissolving in a few minutes and others lasting for over 1 day. This, along with local availability, flavor, cost, and

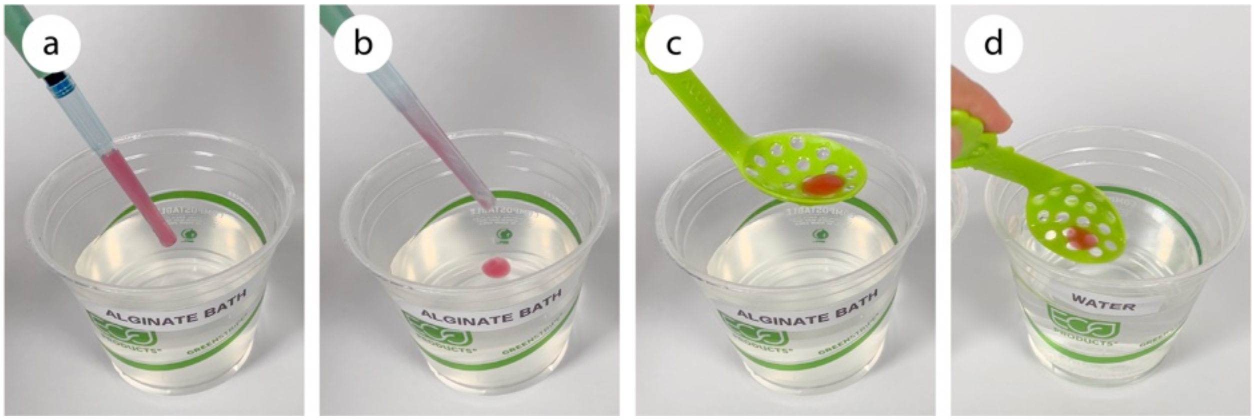


Figure 4.5: Fabrication process of flavor spheres. (a) A pipette is used to drop the sphere into a 0.5% sodium alginate bath. (b) The drop soaks in the bath for up to 45 seconds. (c) The resulting sphere is removed from the alginate bath with a slotted spoon. (d) The sphere is placed into a clean water bath for storage.

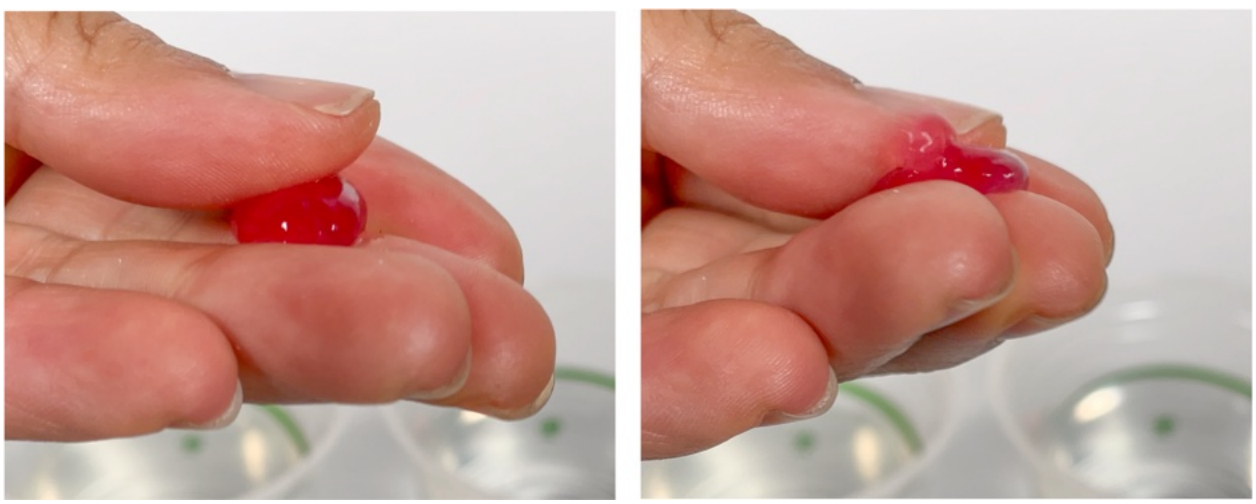


Figure 4.6: Left: Spheres after fabrication may be handled by hand. Right: When squeezed, the calcium alginate film encasing the sphere pops, releasing the internal liquid.

"mouthfeel" are factors that can influence the selection of one wrapping film over another.

Finally, edible glue, denture adhesives, or sticky foods may be used to help hold a finished pouch in place against the cheek, where it rests on the outside of the teeth. In this location, it does not interfere with activities such as chewing, drinking, and talking (see Figure 4.4).

4.4 Characterization

In this section, I present technical characterizations *ex vivo* – that is, outside the mouth – so that I may offer better clarity of the design parameters and capabilities of our system. I have done our best to simulate *in vivo* conditions to give us confidence that our results can be replicated in the mouth. I also tested our system in our own mouths and report preliminary qualitative experiences in Section 4.5. For ex vivo characterization, I use a piece of hydrogel as a stand-in for a human cheek. I follow the recipe for MRI phantoms in [103] to create a hydrogel acoustically matched to human tissue that is composed of agar, $NiCl_2$, $MnCl_2$, NaCl, and water. I do not expect that the powers and pulse lengths used here are intense enough to cause unwanted tissue heating, one of the known possible side effects of ultrasound treatments in medicine [227]. Still, as a sanity check, I add orange thermochromic pigment that turns light green above 86°F (SolarColorDust.com) to our hydrogel to visually ensure that I do not induce areas of dangerously high temperatures in the skin. I pour the hydrogel into molds that result in slices that are 6.7mm thick, corresponding to the average thickness of the human cheek cited in literature [164]. I place the hydrogel layer on top of our ultrasonic transducer, which I encase in an acrylic box that has a circular cutout on its top surface for the emitting surface of the transducer's piezo element. A dab of ultrasound gel is used between the transducer and the hydrogel to improve coupling.

4.4.1 Effects of Sphere Parameters

The length of time that a flavor sphere spends soaking in the sodium alginate bath determines the thickness of its encasing calcium alginate film. I expect that thicker films are stiffer, requiring higher ultrasound excitation voltages to pop. Table 4.1 reports the average measurements of sphere popping threshold for different alginate bath soak times. Spheres are 0.8mL in volume for all soak times listed. Using a stopwatch, I measure soak time as the time between the drop hitting the surface of the bath and it leaving the surface of the bath on the slotted spoon. The popping threshold is determined by placing a sphere on the surface of the artificial skin, resting on the HIFU transducer, and then applying 0.25s pulses of increasing voltage, separated by 5s, until I observe a visible stream of liquid emitting from the sphere.

Soak Time (s)	**Pop Threshold ($V_{P\text{-}P}$)**
5	32
10	37
15	47
20	57
30	66

Table 4.1: Effect of Alginate Bath Soak Time on Ultrasound Voltage Popping Threshold

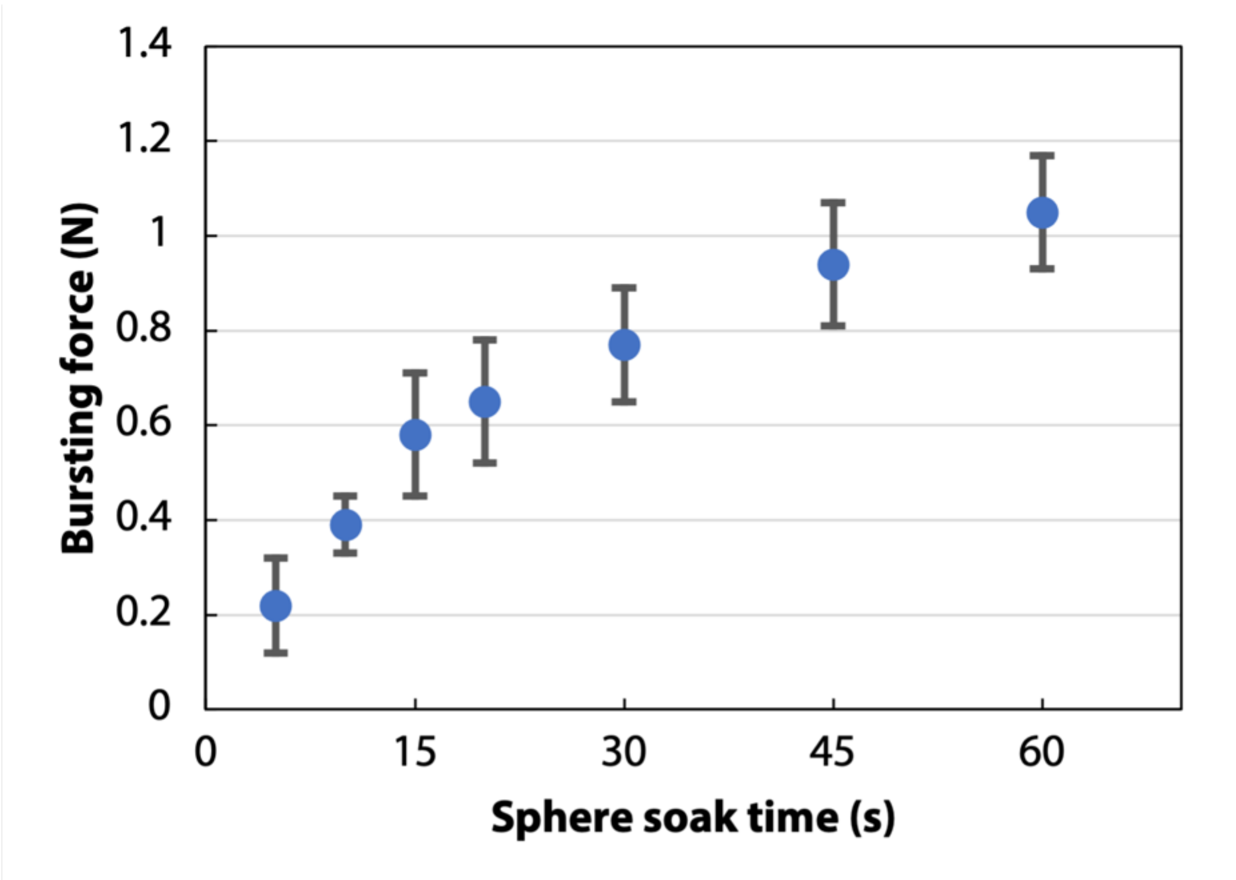


Figure 4.7: Plot of force required to burst spheres vs. soaking time in sodium alginate.

Indeed, I observed that as soak time increases, the popping voltage threshold also increases, with voltages increasing from $32V_{P-P}$ (14W RMS power) to $66V_{P-P}$ (51W RMS power) for spheres soaked for 5-30 seconds.

Additionally, I measured the dependence of the force required to burst spheres on the sodium alginate soaking time. The bursting forces of spheres made for 7 different soaking times in the range of 5 to 60 seconds (10 spheres per condition) were measured by pressing spheres onto a digital force meter until they broke open. The results are plotted in Figure 4.7. The tongue can exert up to ∼16N [334], but the force of the tongue during swallowing is only 0.31N [336]. Thus, spheres can likely indeed be burst with the tongue (or teeth) if there is intention to do so, but using sodium alginate soak times longer than 10s (resulting in spheres that require 0.39N to break), spheres are largely robust against accidental rupture from routine activities such as swallowing.

I also made spheres of different volumes between 0.25mL and 1mL soaked in the alginate bath for 10s, hypothesizing that larger spheres would burst at smaller voltages. Surprisingly, however, I did not observe a repeatable, systematic relationship between popping threshold

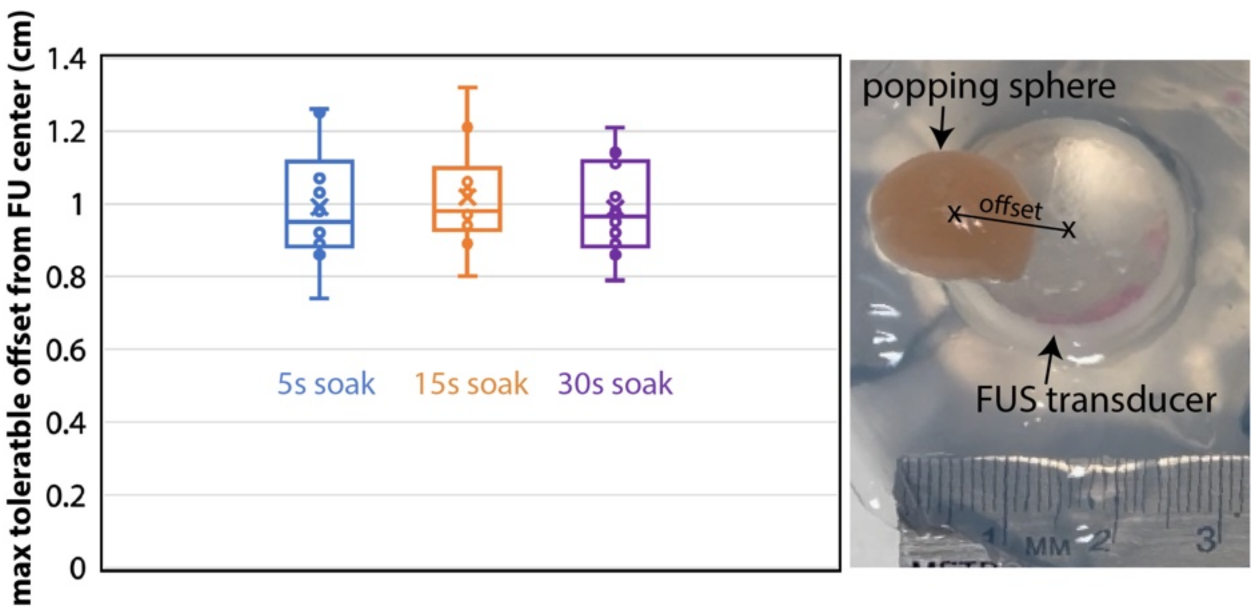


Figure 4.8: The maximum tolerable misalignment of spheres in x-y with respect to the HIFU transducer center is ∼1cm, regardless of sphere soak time.

and sphere size in this range, which I believe is a reasonable balance of having spheres large enough to taste and small enough to be held against the cheek without posing significant discomfort. This may be because popping threshold is more strongly related to alginate bath soak time, and the effect of small variances in soak time from sphere to sphere (from the nature of our manual fabrication and soak time measurement methods) dominate any effect of differences in sphere volume in the range of volumes I tested.

Some liquids, such as cranberry juice, require more guar gum than thicker liquids, such as mango pulp, to achieve the same consistency and result in comparably shaped spheres. Once normalizing for liquid consistency, however, I did not notice a dependence of popping threshold on the type of liquid enclosed in the spheres. I tested cranberry juice, bottled latte (coffee and milk), mango pulp, orange juice, broccoli juice, cola, and 2 different kinds of sports drinks.

4.4.2 Sensitivity of Sphere Placement

I envision Füpop as a system for which the “wearer” will have to place a pouch inside their own mouth. Thus, it is important to understand the tolerable misalignment of spheres with respect to the HIFU transducer. I conducted an experiment in which I placed a sheet of cheek-like hydrogel on an HIFU transducer. I then placed a sphere far away (>2cm) in x-y from the center of the HIFU transducer and incrementally pushed it towards the center of the transducer; meanwhile, I pulsed the transducer with the sphere’s popping threshold voltage. I recorded the “maximum tolerable x-y offset” as the distance between the center of the sphere and the center of the HIFU transducer at the point when the sphere burst. I repeated this for 10 spheres of 3 different alginate soak times (5s, 15s, and 30s). Figure 4.8 plots these results. For 5s, 15s, and 30s soak times, the maximum tolerable offsets were 0.99±0.17cm, 1.02±0.15cm, and 0.99±0.13cm, respectively. Thus, while this suggests that some care is needed when aligning the Füpop pouch inside a mouth to the HIFU transducer outside of the mouth, I believe that it is a reasonable misalignment tolerance that can be managed without the need for specialized jigs for reasonably sized spheres. For reference, spheres of 1mL in volume, which is our estimated maximum size that one might want to use to fit multi-flavor pouches comfortably in the mouth, have radii of approximately 0.62cm. Spheres of 0.6mL in volume have radii of approximately 0.5cm, so for a 3-flavor pouch with 0.6mL spheres (i.e. spheres vary only in soak time), the transducer could be almost completely centered over one of the spheres, and I would expect that the 3 spheres would burst sequentially as expected at their respective threshold voltages. Still, more testing, especially in vivo, could help confirm that spheres in a multi-flavor pouch indeed burst in the intended order across different misalignment cases.

4.4.3 Resistance to Dissolution

I tested our materials for their resistance to inadvertent dissolution by soaking them in a bath of real saliva. Spheres across all soak times remained intact for over 24 hours when stored in a bath of saliva at room temperature. I also soaked 3 different wrapping films – potato starch Oblate discs, rice paper, and grape leaves – in saliva. Potato starch oblate discs took 15 min to break down, and rice paper took 50 min. Grape leaves did not show any sign of dissolving even after 24 hours.

4.4.4 Effect of Ultrasound Power

Driving the HIFU transducer with longer pulses and higher voltages may result in excessive power consumption from the driving electronics as well as risks of heating the skin to uncomfortable temperatures. I thus limit pulse lengths to 0.25s and excitation voltages to $80V_{\text{P-P}}$, corresponding to a RMS power of 90W and skin surface power density 24W/cm^2. This in turn limits the soak time of spheres to 45s, after which point higher powers are needed to pop the spheres. Under these conditions, the artificial skin stays entirely orange, indicating that it does not heat to temperatures above 86°F. The cheek pouch may also be touched with a finger without any discomfort or pain. As previously mentioned, HIFU is used in medical therapies for multiple seconds at a time with much higher powers [227, 269]. For tumor ablation, powers in the thousands of W/cm^2 are typically used [80]. Even for therapeutic cosmetic treatments for lifting soft tissue, HIFU transducers with frequencies of 2-10MHz are typically operated at 50-400W [262] with no reports of adverse effects or severe pain [370].

Figure 4.9 shows a series of images of latte spheres with a 15s soak time under different excitation voltages. As voltage increases and approaches the popping threshold, the sphere

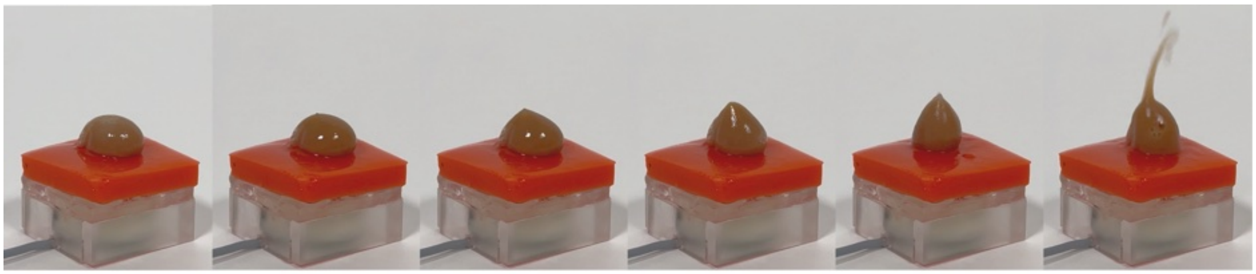


Figure 4.9: A series of latte (coffee and milk) spheres under excitation with different peak-to-peak transducer voltages. All spheres are 0.8mL in volume with a 14s alginate bath soak time.

becomes more misshapen by the ultrasonic excitation until the force is finally great enough to burst it. For the sphere in the figure, I expect that the threshold voltage (from Table 4.1) is between 47 and 57$V_{P\text{-}P}$. For voltages applied significantly above the threshold voltage, the sphere explodes violently, spewing its liquid in a dramatic spout, as seen in the last image of Figure 4.9, when 60$V_{P\text{-}P}$ is applied. Below the threshold voltage, the ultrasonic energy pushes the liquid in the sphere towards the focal area away from the cheek, forcing the sphere into a pointed droplet shape. When I rest a fingertip on the sphere and activate the transducer below the popping threshold, I perceive the bulging of the sphere as a feeling akin to a light prick. Of course, more quantitative and qualitative data is needed to characterize these pressures and the resulting in-mouth sensations, but I are encouraged by this preliminary data and believe that I may be able to take advantage of the different pressures exerted by the spheres at voltages below the popping threshold to create different in-mouth textural sensations, which could potentially be reproduced repeatedly on the fly over the course of multiple minutes and even hours.

4.4.5 In-Mouth Testing

Here I report on preliminary testing that I conducted on myself to verify that Füpop can operate inside a real human mouth. The pouch was placed by opening the mouth, gently pressing on an HIFU transducer placed on the outside of the cheek, and using the resulting indentation on the inside of the mouth as a placement guide – while this likely did not result in exact centering of the pouch with respect to the transducer, as noted in Section 4.2, spheres may be misaligned by up to 1cm, so this manual, "best guess" method was sufficient. Some care must be taken to ensure that the spheres do not prematurely pop during handling and insertion into the mouth, but once positioned in the mouth against the cheek, the edible portion of Füpop is fairly robust to most normal disturbances. One co-author kept a pouch containing 3 spheres inside their mouth against the cheek for 45 minutes, periodically drinking hot tea and cold water, swallowing, making chewing motions, and talking. The feeling of the pouch was foreign and somewhat uncomfortable at first, and the co-author reported feeling tempted to play with it with their tongue. However, they quickly became accustomed to the sensation within a few minutes and found the pouch largely easy to ignore. At the end of the 45 minutes, no spheres were ruptured, and the co-author did not report tasting leaking from any of the liquids contained in the spheres. This is unsurprising, as the calcium alginate film that forms around each sphere is insoluble in water, does not melt at temperatures below 100°C, and is mechanically robust, being known for its ability to last for days as a wound dressing [167]. I made spheres containing cranberry juice, mango pulp, broccoli juice, cola, latte, and various sports drinks, and all co-authors were able to distinguish among the flavors and successfully identify them when they were popped inside the mouth, with only some confusion existing around the artificial flavor of the sports drinks. I again expected this, since the calcium lactate and guar gum added to the liquids are both tasteless and are added in very small quantities, and the liquids I tested are naturally distinctive from one another.

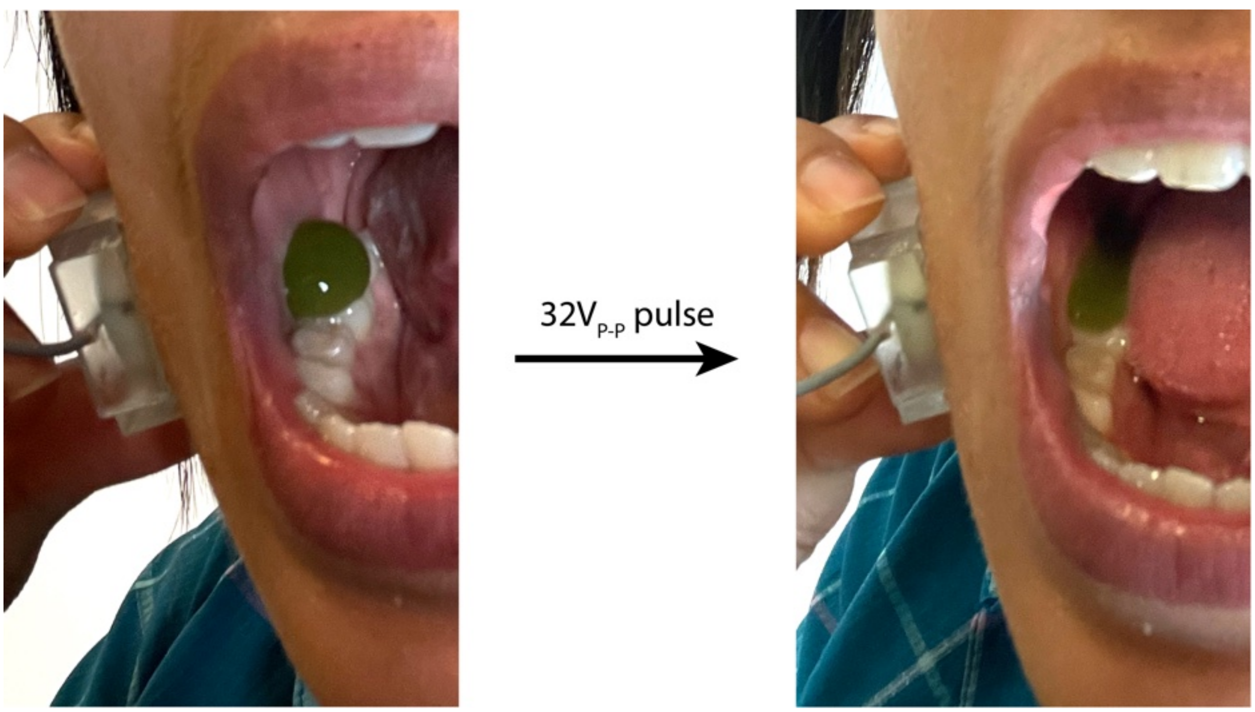


Figure 4.10: A sphere of broccoli juice held against a cheek inside the mouth is burst with a HIFU transducer held on the opposite side of the cheek, excited with a $32V_{P-P}$ 0.25s pulse.

Finally, I placed a single sphere filled with broccoli juice in my mouth against my cheek and centered a HIFU transducer on the other side, pressing the transducer against the outside of the cheek to help align it with the sphere on the inside (see Figure 4.10). This took some trial and error, suggesting that we may need a more robust alignment scheme in a future user study. Once the transducer was aligned, a $32V_{P-P}$ 0.25s pulse was applied, resulting in the sphere bursting inside the mouth, as confirmed visually. I tasted broccoli and did not notice any pain, noise, or sensation other than taste to indicate that the broccoli sphere had burst.

4.5 Choreographing Flavor Sequences

As described in Section 4.1, spheres with distinct enough alginate soak times can be reliably sequentially burst with different HIFU voltages. A designer may thus "choreograph" a sequence of flavors to be delivered for a user by packaging together different flavor spheres each made with different alginate soak times. The spheres do not visually differ from one another besides being different in color, so a user cannot predict what order the spheres will burst in by merely looking at the edible pouch.

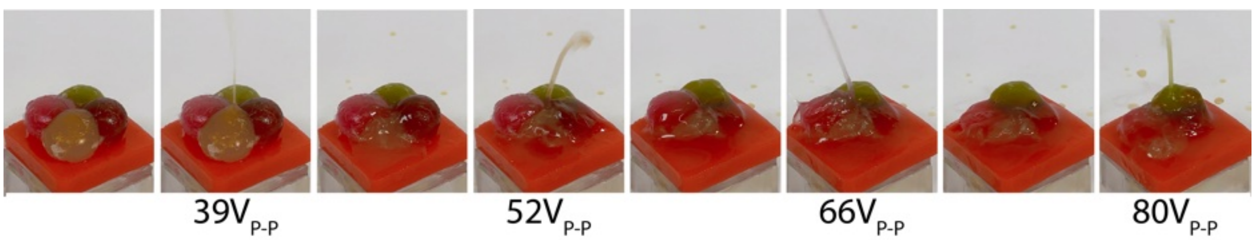


Figure 4.11: A Füpop pouch containing 4 spheres with different calcium alginate film thicknesses. In order of increasing thickness: mango pulp (yellow), cola (brown), cranberry juice (pink), and broccoli juice (green). These spheres may be popped sequentially using increasing ultrasound pulse intensities.

An ex vivo demonstration of this is illustrated in Figure 4.11. I create a 4-flavor pouch containing a mango pulp sphere soaked in alginate for 5s, a cola sphere soaked for 15s, a cranberry juice sphere soaked for 25s, and a broccoli juice sphere soaked for 35s. The spheres are wrapped in an potato starch Oblate disc, with the excess film cut away with a blade. Per the characterization presented previously, I expect the mango sphere to selective burst under excitation voltages higher than $32V_{P\text{-}P}$ but lower than $47V_{P\text{-}P}$, the cola sphere to selectively burst with voltages $47V_{P\text{-}P}$ to $57V_{P\text{-}P}$, the cranberry sphere to selectively burst with voltages $57V_{P\text{-}P}$ to $72V_{P\text{-}P}$, and the broccoli sphere to burst above $72V_{P\text{-}P}$. Indeed, as seen in Figure 4.11, when the pouch is placed on our ex vivo testing setup, I use 4 pulses of increasing voltage to burst each sphere one at a time, with the expected order of mango, cola, broccoli, and cranberry flavors being released. At each voltage step, a single colored stream can be observed coming from the packet. Between pulses, I manually check remaining spheres by lightly pressing on them to ensure that they are indeed still intact.

To verify the selectivity of bursting spheres of different voltages and also test the effect of the presence of teeth against the backside of the spheres, I fabricated 20 pouches with Oblate potato starch discs, each containing 3 spheres with 3 different sodium alginate soak times – 5s, 15s, and 30s. I placed the pouch on the inside of the cheek of a dental typodont model (an anatomical model mimicking the properties of human teeth and tissue that is

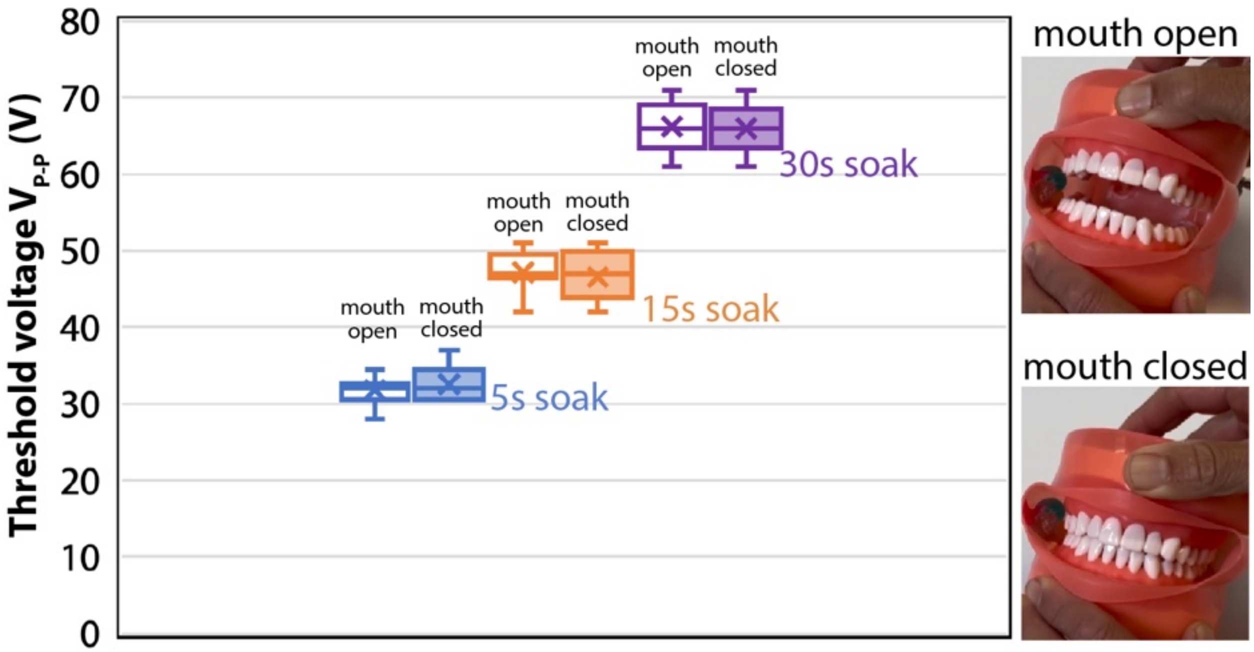


Figure 4.12: Bursting threshold voltage for spheres in a Füpop pouch containing spheres soaked in alginate for 5s, 15s, and 30s. Threshold voltage does not depend on whether the mouth is open or closed.

used for practice in clinical settings for dental and hygienist students) with denture adhesive (Polident). For 10 pouches, I held the mouth of the model open, and for the other 10 pouches, I kept the mouth closed (see Figure 4.12). For each pouch, I placed the focused ultrasound transducer on the outside of the cheek and applied pulses of increasing intensity until a sphere burst. I continued increasing the intensity until all 3 spheres in the pouch had burst. The results are plotted in Figure 4.12. For spheres soaked for 5s, the threshold voltage was 31.8±1.8V with the mouth open and 32.5±2.0V with the mouth closed. For spheres soaked for 15s, the threshold voltage was 47.1±2.4V with the mouth open and 46.6±3.1V with the mouth closed. For spheres soaked for 30s, the threshold voltage was 66.2±3.1V with the mouth open and 66.0±2.7V with the mouth closed. In all cases, the spheres burst in the order expected (i.e. in order of increasing soak time), and there was no significant difference in threshold voltages observed between the mouth open and mouth closed conditions.

4.6 Discussion

4.6.1 Envisioned Applications

this chapter focuses on the characterization and implementation of Füpop as a technological framework that can enable real-time interaction with taste and the delivery of food in the mouth. With future in-depth user studies, I believe that Füpop will be a valuable addition to the growing toolbox of technologies that the HFI community has developed to foster play and social connection in the experience of eating [237, 359, 358, 8]. I envision that Füpop can enable programmable multi-course experiences (albeit miniature ones) that can either be triggered on their own or along with a normal meal, enhancing or altering flavors. The timing of the ultrasound pulses that release each sphere may be regimented or programmed to be random. With many different variations possible, Füpop is a technological platform that eating experience designers can leverage.

4.6.1.1 Tasty tangible telecommunication

Füpop opens up doors for technologies that stimulate our mouth along with, or in lieu of, the currently more common stimuli to our eyes, ears, hands, and nose. It may be seamlessly integrated with existing hardware commonly used for long-distance communication as part of a novel experience around taste interactions. An illustration of example potential integrations is shown in Figure **??**. Headphones and cell phones, for example, are ideal candidates for Füpop, as they are already positioned on or near the cheek when conventionally used. We might imagine that Füpop's electronics can be readily integrated into such hardware or be offered as a clip-on accessory. To offer placement flexibility, the hardware extensions for Füpop may be made adjustable or conformal, and/or temporary adhesives, such as Vetbond Tissue Adhesive (3M), could be used when appropriate to further secure Füpop's transducer. However, since as discussed in Section 4.2, up to ∼1cm of misalignment between the spheres and the HIFU transducer is permitted, adhesives are likely unnecessary.

I envision that partners or close friends could exchange Füpop pouches and send one another choreographed flavor experiences for tangible telepresence interactions or surprising gifts. For example, Alice might gift her friend Bob a package containing a clip-on HIFU transducer for Bob's smartphone, a Füpop pouch, and a document illustrating how to place the pouch inside the mouth and instructing Bob to call a certain number on his phone. Bob secures the HIFU transducer onto his phone, places the pouch inside his mouth, calls the number, and is delighted to hear a voice message from Alice reminiscing on their shared experience during a recent cooking class. Alice has programmed the transducer to sequentially trigger the release of tomato soup, cheese fondue, and chocolate custard spheres, which she made herself with recipes from the cooking class, that are synced to her voice message as she describes each course. Such"taste messages" could be a way to share the sequential experience of exotic flavors and foods encountered during travel, evoke a certain mood, or create a new kind of suspenseful experience for entertainment that are difficult to replicate with non-technological means (i.e. simply telling someone to eat a series of snacks).

Figure 4.13: Mock-ups of Füpop electronics integrated into a cell phone, an audio headset, and a head-mounted display.

4.6.1.2 Multimodality and immersive virtual reality

Similarly, Füpop may find use in virtual and/or augmented reality (VR/AR) applications. Aligning what the user sees with what they taste (or perceive through other senses) can increase their feeling of immersion and presence in a virtual world [379]. Conversely, Füpop may even be used to intentionally create sensory misalignment, an effect where a user sees or feels one thing and tastes another. Sensory misalignment can create illusions across different senses that can be taken advantage to craft novel, unusual experiences [218]. Whereas previous technologies often use organic materials that are not commonly "food," even if non-toxic, I present a system which allows immersive technologies to leverage the rich diversity and complexity of the flavors and foods already in our world. While Füpop in its current embodiment does not support re-programming the order and content of flavors on the fly, we might imagine Füpop augmenting guided VR tours that take users through a pre-determined walkthrough of a space, with "real food"-based flavor deliveries via Füpop enhancing the visual experience along the way.

4.6.1.3 Expanded embodiments

While I mostly discuss the possibility of sequential flavor delivery, spheres of the same size and film thickness may be packed into pouches to be popped simultaneously to create the mixing of flavors and potentially even new textures or auditory experiences. Spheres may be simply filled with carbonated beverages that fizz in the mouth, or they may be filled with liquids that react with one another to create dramatic foaming, temperature changes, or other sensations in the mouth that are not strictly based on the stimulation of taste buds on the tongue. With many different combinations of flavors, textures, and other in-mouth sensations possible, Füpop can be used to augment the experience of eating a dish, transforming it into a personalized, dynamic experience that changes with (or even within) each bite. With further development and experimentation, Füpop may also find applications for medicine and personal health. For instance, it could be integrated into taste assessment or retraining protocols for patients who experience a loss of taste due to an infection or nutritional deficiency.

Finally, the technology of Füpop may also be used outside the mouth as well, both within the food "production" HFI domain and beyond food-related contexts. For instance, ultrasound transducers may be mounted to the bottom of plates beneath poppable spheres of interest, enabling playful interactions at the meal table that could even have multiple participants. Focused ultrasonic transducers, coupled with spherificated liquids, could also be used to induce surprising destruction events as part of the "unmaking" of a larger structure, encouraging viewers to reflect upon the temporality and degradability of the materials that they possess [304].

4.6.2 Safety

There are naturally practical safety considerations that need to be carefully characterized with a large-scale user study before the commercial or mass deployment of Füpop or a similar system. For example, the flavor spheres and edible pouch could potentially present choking hazards. Similarly, while I carefully limit the power of the focused ultrasound transducer used here in accordance with available clinical studies in literature, I ultimately use the transducer in a novel way that differs from documented medical uses. Thus, more rigorous clinical evaluation is needed to ensure that users are not subject to risks like burning and unwanted tissue ablation. Nonetheless, based on our technical characterization, available clinical studies in literature, and personal experience, all of which I discussed previously, I do not believe that Füpop presents more danger than existing research prototypes for influencing taste, smell, or touch.

4.6.3 Ethics

In addition to safety, ethics are an inherent consideration when it comes to designing Füpop or other HFI experiences. In many potential applications for Füpop, the designer and user are not the same person, and in fact, the user is not necessarily aware of the flavors, or order of flavors, that they may experience. Among other concerns that arise from this, the designer may intentionally or unintentionally create unpleasant (e.g. nausea-inducing or foul-tasting) flavors, or potentially even dangerous and life-threatening experiences (e.g. using ingredients that the user is allergic to, using spoiled ingredients, or creating extreme exothermic reactions in the mouth). Before putting a Füpop pouch into their mouth, the user must inherently trust that the subsequent experience aligns with their individual tolerance and that appropriate safety and sanitation precautions were taken with the handling of ingredients during fabrication.

4.6.4 An Ally to Sustainability

With the increasingly pressing climate crisis looming among us, we are obligated to reflect upon environmental considerations when introducing a new technology like Füpop. While there are many different schemes to make interactive systems more sustainable, one well regarded principle, as discussed previously, is to select the right materials – ones that are created, used, and degraded with the lowest carbon footprint possible [182]. Füpop is admittedly not a system that utilizes solely degradable materials, but I still believe that our approach of utilizing as many edible components as possible to invoke tastes while also minimizing the footprint of the necessary electronics is a step in the right direction towards creating sustainable systems. This is not to say using edible materials alone qualifies a system as "sustainable." Care must still be taken to select edible ingredients that require minimal resources to grow and process, are easily stored and transported, and do not generate excessive waste, among many other considerations [50]. Nevertheless, when designing technologies for eating and taste, prioritizing edible materials over plastics or other non-degradable electronics simultaneously provides the benefit of offering nutritive, real food flavors instead of synthetic ones while also ensuring that the resulting system is at least in part made from easily degradable components that do not create more landfill. In this way, I see Füpop as an *ally* to sustainability. To further decrease the environmental impact of Füpop, we can prioritize local ingredients and minimally processed foods, for instance choosing fruit and vegetable juices over soda and sports drinks.

Furthermore, as previously mentioned, Füpop may be used for ephemeral user interfaces [316] or unmaking experiences, which I discuss in Chapter 7 as a way to link invention with disposal and imbue value, on top of merely eco-friendliness, to motivate the more widespread use of degradable materials. The transient nature of the foods and flavors that Füpop experiences bring may be employed to develop systems that exhibit interesting unmaking effects, encouraging users to reflect upon the sustainability of their eating practices and food choices.

In the near future, I envision being able to create systems that are edible in their entirety, without the need for external, non-degradable electronics of any kind. Materials science and HCI researchers alike are rapidly uncovering material candidates for fully edible functional electronics [108, 382, 298], as well as edible electrical energy storage devices to power them [309].

4.7 Limitations and Future Work

4.7.1 Future User Studies

There are notable limitations of Füpop, some of which future work can certainly address, and others of which are perhaps inherent to the approach and must be carefully taken into consideration when designing experiences with Füpop. This chapter focuses on presenting a characterized novel technical platform for HFI designers to build upon and explore user experiences with. I acknowledge that a user study is needed to understand how Füpop is in fact perceived by people and how individual variables, such as cheek thickness, may affect the parameters of our system. Deploying Füpop in real human mouths will also be pivotal in testing our hypotheses, based on the ex vivo characterizations presented in this chapter, that I can reliably create multi-flavor choreographed experiences with Füpop without specialized alignment jigs. In addition, design probes, trial deployments, and qualitative research could be undertaken to investigate how the interactions I introduce can fit into real contexts and practical situations.

4.7.2 Choreographing Experiences On the Fly

Furthermore, one technical limitation of this system as presented is that while the timing of the bursting of each flavor sphere can be controlled by an external device on the fly, the order in which the spheres burst is pre-determined by the designer, since spheres with thinner alginate films will always burst before those with thicker alginate films. While this still enables the applications I describe above to be implemented to some extent, it constrains a designed application to be choreographed ahead of time and does not support arbitrary flavors being delivered in an arbitrary order. One possible future direction that could potentially overcome this limitation is to investigate how we might leverage different resonant frequencies corresponding to different sphere geometries. A wide-band piezoelectric transducer capable of emitting energy at multiple different frequencies could be used for this. A specific sphere may then be selectively burst with the transducer excited at the resonant frequency of that sphere, enabling spheres to be burst in an arbitrary order. Alternatively, we could make arrays of HIFU transducers that are each centered on specific spheres on the other side of the cheek, allowing specific spheres to be excited and popped simply by activating the corresponding transducer. Arrays, while complicating the electronics need to drive them and perhaps necessitating additional calibration schemes, could also help mitigate transducer-to-pouch alignment difficulties. We may draw inspiration from work in materials science to make such arrays soft and conformable [391].

4.7.3 Considerations in Using Real Food

Additionally, one characteristic of Füpop is that a limited number of flavors is available to a user for a given experience. There are only so many spheres that one can fit comfortably in the mouth and that can exist within a single transducer's focal area; moreover, a sphere cannot be revived once it is popped and its flavor is released into the mouth. In some ways, this is a limitation in contrast to approaches such as Miyashita's concept of electrophoretic "taste displays," which offer lickable sticks of basis flavors that can theoretically blend to simulate a large spectrum of flavors across arbitrarily long periods of time [231, 232]. On the other hand, this is a unique characteristic that can alternatively be considered an asset. Unlike electrophoretic taste displays, the ingredients used in Füpop are fully edible and nutritive. This by default lends itself to more authentic flavor deliveries. If the designer wishes to deliver the taste of a cranberry, they can simply make a sphere filled with cranberry juice instead of perfecting and testing the right recipe of basis flavors to concoct a sufficiently convincing substitute. Füpop's flavors do not just offer the taste of food; they *are* food. Thus, Füpop may be useful in developing playful and positive associations with both the taste and consumption of healthy real vegetable juices, for instance.

4.8 Conclusion

Following the systems-level strategy for developing wirelessly powered backyard-degradable interactive electronics that I introduced in the previous chapter and capitalizing on the inherent backyard-degradability of food, this chapter offers Füpop, a novel technology that opens the door for computational flavor experiences based on real food that can be activated without the need for wires or tubes entering the mouth. In comparison to existing HFI systems, Füpop's flavors are inherently real, not imitative, and experiences with Füpop do not require that the mouth is propped open to allow for tubes or wires. Füpop utilizes a small focused ultrasound transducer outside the mouth to release a programmed sequence of liquid food spheres that may rest unobtrusively inside the mouth. I have shared ex vivo characterization demonstrating a few of the design parameters of Füpop and also a preliminary in vivo test demonstrating elements of Füpop operating in a real human mouth. As researchers develop more edible, functional materials, I foresee the development of more capable systems that can even exist entirely inside the mouth without the need for external electronics. In the meantime, there are many opportunities to design hybrid systems that build upon advances in not only traditional electronics but also culinary science and gastronomy. I see Füpop as a union of these disparate worlds, and I hope that this work offers inspiration for future designers to develop more such systems to craft novel, more sustainable taste experiences with the rich food cultures and traditions already present in the world.

Chapter 5

Vims: Customizable Electrical Energy Storage

The previous two chapters presented backyard-degradable modules that leverage wireless energy transmission from non-degradable, conventional electronics. The next two chapters present backyard-degradable electronic components, with the end goal of being able to create standalone systems that do not rely on wireless coupling to conventional electronics to operate. This chapter in particular presents the design and evaluation of *Vims*, a backyard-degradable energy storage module, a critical element for the development of standalone backyard-degradable interactive systems that do not require the wireless power transfer strategies presented thus far [1]. As I will discuss, *Vims* not only degrade in garden soil in a few months but also pave the way for new design possibilities when prototyping low-power electronics.

Providing electrical power is essential for nearly all interactive technologies, yet it often remains an afterthought. Some designs handwave power altogether as an "exercise for later." Others hastily string together batteries to meet the system's electrical requirements, enclosing them in whatever box fits. *Vims* offers a new approach – it elevates power as a first-class design element; it frees power from being a series of discrete elements, instead catering to exact requirements; it enables power to take on new, flexible forms; it is fabricated using low-cost, accessible materials and technologies; finally, it advances sustainability by being rechargeable, non-toxic, edible, and compostable. *Vims* are backyard-degradable battery alternatives that rapidly charge and can power small applications for hours. I present *Vims*, detail their characteristics, offer design guidelines for their fabrication, and explore their use in applications spanning prototyping, fashion, and food, including novel systems that are entirely backyard-degradable and edible.

[1] Large portions of this chapter have previously appeared in the 2023 ACM CHI proceedings. The original citation is as follows. Katherine Wei Song and Eric Paulos. 2023. Vim: Customizable, Decomposable Electrical Energy Storage. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, Article 180, 1–18 [309].

5.1 Introduction

There is a great disconnect between the design of portable interactive electronics and the design of the energy storage systems that power them. Consider the following: Alice is a designer who wishes to create a small interactive electronic ring to wear for a few hours at an upcoming special event. She begins by prototyping on a benchtop, using a power supply to power her electronics and focusing on refining her desired interactions and aesthetic elements, which she can iteratively prototype quickly. Once satisfied, Alice makes the appropriate electrical measurements to estimate the power consumption of her system. The system turns out to be very low power, requiring only 1V and consuming at most 1mA. Looking through an online catalogue, Alice finds that the smallest battery that can suit her needs is a 3.7V, 110mAh lithium ion battery that costs $6 (USD) [2]. It will arrive in 2-5 days. While the battery is relatively small – half the size of a thumb – it is still large for Alice's on-finger application and will power the system almost 100 times longer than necessary. Alice is further disappointed to realize that after the event, she will have no use for the battery, and it will simply sit in her drawer and gather dust alongside her growing collection of old batteries. While waiting for the battery to arrive, Alice adjusts her design, increasing its size substantially to accommodate, hide, and protect the battery.

Although this is a hypothetical scenario, I believe that it is a relatable one that illustrates the dissonance that arises when making a design that is intended to be portable actually portable. For electronics prototypers, makers, and hobbyists, power is often a mere afterthought that is designed around late in the design process. At that point, a designer may find themselves constrained by the limited, discretized options that exist commercially. Off-the-shelf batteries, the most common form of energy storage for portable electronics, can be cumbersome to work around. Without expensive customization, they are limited in form factor options, existing as cylinders or blocks that are almost always rigid. They can be bulky eyesores, especially when multiple units are haphazardly strung together, posing a thorn for the aesthetics or wearability of a design. It is no wonder that the batteries or bulky power supplies behind the scenes in research prototypes of many impressive interactive technologies are often only very fleetingly mentioned in papers or are sometimes left out of the discussion and figures entirely.

Some systems have been designed to avoid energy storage altogether, harvesting small amounts of energy from the environment to directly power ultra-low-power systems [13, 15, 14]. Still others avoid energy storage by utilizing near-field wireless power transfer from wireless chargers [308] and mobile devices [121, 70, 68]. Nonetheless, on-board energy storage is unavoidable for several interactive systems that require more power than can be continuously harvested ambiently (i.e. >1mW) or that need to operate in situations where wireless power transfer is unavailable or inconvenient. Unfortunately, the industry goals of developing batteries that endure for as long as possible are often not aligned with the needs of small-scale designs. Conventional lithium ion batteries are well suited for phones,

[2] https://www.sparkfun.com/products/13853

laptops, and other power-intensive devices. However, for other lower-power or temporary interactive systems – both existing and yet to be developed – using such high-capacity batteries is arguably excessive. These are the applications that I target in this chapter. In this domain, we can free ourselves of the constraints of performance optimization and capacity maximization, instead experimenting with more accessible, low-cost, non-toxic, and customizable materials that designers can use to draft their own energy storage modules that cater exactly to their needs.

Addressing the current inability to customize energy storage for our designs is more than just a matter of enabling new aesthetic and functional possibilities. Batteries present a serious sustainability problem and are some of the most environmentally hazardous components of electronic interactive systems. They rely on toxic metals, such as cadmium, lead, or lithium, that are extracted through resource-intensive processes and must be carefully recycled or contained at end of life. Waste handling is a particularly troublesome challenge for not only individual designers but also electric car manufacturers and consumer electronics companies as they strive for more sustainable practices. Lithium ion batteries that are improperly disposed of in regular landfills can cause fires, endangering nearby communities [3]. The lack of sustainable energy storage alternatives is a substantial obstacle in the path of the collective efforts among the Human-Computer Interaction (HCI) community of makers to create eco-friendly interactive systems [182, 22, 21, 340, 16, 308].

Rejecting the idea that energy storage remains an afterthought in the design process, I propose instead that it takes a front seat early on, alongside the other elements of an interactive system. Resonating with calls in the HCI community for more eco-friendly materials and design practices, I further insist that this be done by foregrounding sustainability and prioritizing materials that are biological, renewable, and *backyard-degradable* – that is, easily degradable without specialized industrial conditions. I seek to enable this by presenting *Vims*[3]: fully backyard-degradable energy storage elements that can be rapidly charged and recharged and that hold power for days. Cheap and safe enough to fabricate at home, *Vims* are capable of powering interactive systems in applications spanning fashion, health, food, and more. *Vims*, while low performance by industry standards, present three key advantages over commercially available energy storage for the HCI community. First, they are made with low-cost, accessible materials and technologies. Secondly, they are thin, conformable, and customizable in form factor, enabling a new degree of design flexibility when prototyping. Finally, they degrade under backyard conditions, greatly reducing the resource cost and complexity of disposal. This in turn enables new kinds of interactive electronics that are also completely backyard-degradable. In the rest of this chapter, I detail the following contributions:

- Adaptable, accessible guidelines for designing *Vims*
- The detailed fabrication and characterization of an exemplar *Vim*

[3] The Oxford English Dictionary defines *vim* as: force or vigour, energy, 'go'

- Demonstrations and discussion that highlight the functionality and advantages of customizable, backyard-degradable energy storage

5.2 Related Work

This chapter draws inspiration from a rich body of research in battery-free systems and materials for sustainable design. Here, I summarize prior work in these areas and describe how this chapter is situated with respect to existing approaches.

5.2.1 Battery-Free Systems

As discussed, batteries are arguably one of the most challenging components to make degradable. One approach, which *Vims* is based on and is the focus of the Operating Principles section of this chapter, is to instead leverage supercapacitors. Supercapacitors have fundamentally different electrical characteristics from batteries and would thus necessitate new electronic design schemes, but they are much more feasible to make backyard-degradable. Still, it's important to note that an alternate promising strategy for simultaneously sidestepping the energy storage problem and reducing electronic waste lies in the creation of self-sustaining and battery-free systems. Researchers have discovered methods to eliminate on-board batteries by engineering systems that can be powered wirelessly. Inductive chargers [226, 319, 308, 270] and near-field communication (NFC) [70, 68, 347, 121, 388] have been successfully used to wirelessly power interactive systems across small (centimeter-scale) gaps. Large-scale wireless chargers can be integrated into surfaces [380, 317] and even clothing worn on the body [318], extending the breadth of scenarios for which wireless power transfer is possible. Using ultrasound, the working range of wireless power transfer may be extended even farther; Gonzalez et al. successfully used ultrasound transmitters to power micromotors, buzzers, and LEDs from almost a meter away [236]. Still, in general, most schemes such as these are effective solutions only if wireless chargers, mobile devices, or other wireless power transmitters are nearby, which might not be the case in, for instance, remote or unmanned environments.

For some interactions, the act of bringing a device near a wireless power transmitter is unnatural or not always practical, and for these, researchers have developed alternate power schemes. There have been demonstrations of ultra-low-power (<1mW) systems that can communicate solely using the power from ambient RF, a mechanism called ambient backscatter [202]. Electromagnetic energy from TV signals [202, 259], WiFi [26, 393, 392], Bluetooth [392], and AM/FM radio [352, 351, 15, 13, 14] may be employed for such systems. Ambient backscatter has enabled self-sustaining, low-cost systems for the sensing and communication of audio and touch, and it has been integrated with other forms of energy harvesting as well. For example, Arora et al. presented a a self-powered microphone that runs on a triboelectric nanogenerator harvesting energy from vibrations [15] and communicates using analog backscatter [13]. Zhang et al. presented *Sozu*, a system that harvests mechanical, thermal, solar, and electromagnetic energy to power an RF broadcast that can in turn be received by a remote device [395]. Hand cranking may also be used to power small systems [207]. Interactive Generator [17] used the manual rotation of a servomotor to generate power for various electronic interactions and also provide haptic feedback to the user. Hand cranking can generate more instantaneous power than nanogenerators can, but a downside for both is that without integrated energy storage, power is supplied for only as long as the cranking or other activity from which energy is harvested continues. For those applications that are low power enough to operate solely on ambient RF waves, which are reliably available in many locations around the world, this may not be a major concern, but other applications still require on-board energy storage to operate without interruption and as intended.

Our work adds yet another option to this increasingly rich pool of techniques and is especially attractive for the many applications that require more power than that which can be harvested from the environment continuously. After presenting the design, characterization, and example applications of *Vims*, I also discuss the considerations involved in deciding if *Vims* are indeed the most suitable option – both in terms of performance and environmental impact – for a given system.

5.2.2 Materials for Sustainable Electronics

As discussed in Chapter 2, this is by no means the first time HCI researchers have called for more sustainable design and prototyping [28, 213, 182, 33, 72, 265]. Upcycling [40, 111], "salvage fabrication," [66], "unmaking" [304], and fabrication with disassembly in mind [381] are just a few promoted practices that aim to reduce waste by supporting prolonged material use and reuse. Selecting the right materials in the first place is also an important component of sustainable design [182], and in that regard, there have been many exciting recent developments as well. As previously discussed, mycelium has been posed as a replacement for conventional plastics in many applications and boasts the benefits of being growable by an amateur maker, backyard-degradable, moldable, and millable [152, 339, 340, 367]. Beyond mycelium, flax fiber and poly-vinyl alcohol (PVA) are other backyard-degradable materials – dissolvable in water, in fact – that may be used as substrates and enclosure materials for electronics [16]. Food-grade bioplastics [22] and biomaterial made from compost [21], which can incorporate interactive elements such as photochromic or thermochromic inks, have also been demonstrated as viable materials for yet other eco-friendly designs.

Still, there remains much work to be done when it comes to making sustainable interactive electronics. While the aforementioned materials are backyard-degradable, they are not electrically active. Thus, any added circuitry must be manually separated from their degradable substrates and enclosures if they are to be reused, and once they have reached the end of their life, their disposal is still environmentally problematic. As mentioned in Chapter 2, researchers across multiple disciplines beyond HCI have been actively developing for new, readily degradable materials and devices, although the focus is often on performance and not on accessible fabrication workflows.

As I subsequently discuss, *Vims* are functionally supercapacitors – capacitive structures that store charge electrostatically. Supercapacitors are known for their ability to charge and discharge quickly and their prolonged lifetime in comparison to batteries, making them valuable for applications such as regenerative braking [288, 263]. Making eco-friendly supercapacitors is the subject of much research in materials science and traditional engineering disciplines [77, 141, 27, 212, 119, 194, 384, 2]. However, while these approaches replace at least one conventional layer with a natural material possessing a lower carbon footprint, they still utilize some expensive and toxic materials, such as nano-engineered materials and acrylamide [212, 119, 384, 2], or specialized processes, such as high-temperature heating under inert or vacuum conditions [27, 212, 384]. These cannot be simply ported into a makerspace or otherwise accessible fabrication environment. This is not to say that Do-It-Yourself (DIY) methods do not exist at all, however. In recent years, demonstrations of DIY supercapacitors have cropped up on online platforms, such as YouTube [43, 178, 243, 311], allowing hobbyists to begin to take more control over their energy storage designs with a simple web search. Potato slices, or even whole potatoes, can also be used as batteries when paired with copper and zinc electrodes [97, 1]. Although such designs do share a subset of materials with the *Vims* that I present, like the aforementioned research papers, these DIY demonstrations still rely on non-backyard-degradable components, such as steel or aluminum plates, plastic enclosures, copper wires, and metal nails. Additionally, they are often bulky and not adaptable to arbitrary surfaces, limiting their applications.

One notable demonstration of a backyard-degradable supercapacitor made without exotic techniques or materials is a paper by Wang et al. in *Advanced Materials Technologies*. The authors reported supercapacitors made from food items that, when connected in series, can power a small endoscopic camera for 10 minutes [357]. *Vims* improve upon Wang's supercapacitors in terms of both performance – extending working time from minutes to hours and days – and design customizability. I offer accessible design principles that can be easily followed and adapted for widespread explorations, as well as a set of technical characterizations and design applications more relevant to the HCI community.

5.3 *Vims* Operating Principles

Vims are electrical double layer supercapacitors (EDLCs) that store energy at two layer interfaces within a multi-layer stack (Figure 5.1). To enable successful material experimentation within my design, it is necessary to first understand the basic operating principles of supercapacitors. A regular capacitor comprises two conductive electrodes separated by a solid insulator. When a voltage is applied between the two electrodes, initially there is a measurable current between the two electrodes, but charges quickly accumulate at the interfaces between the electrodes and the insulator. As the charges accumulate, current ceases to flow between the electrodes. When the voltage source is removed, a capacitor's stored charge can discharge through another connected circuit, supplying a limited amount of current. Capacitors are used in this way for filtering unwanted high frequency noise and stabilizing circuits.

In comparison, a supercapacitor comprises two conductive electrodes separated from one another by a liquid or gelatinous electrolyte that is abundant with mobile ions. The electrode material in a supercapacitor is selected to be very porous in order to maximize contact area with the electrolyte. This allows supercapacitors to have a higher charge storage density in comparison to a regular capacitor, but this comes at a slight conductivity cost. Therefore, non-porous, highly conductive current collector layers are usually added to the outsides of the electrodes to connect the supercapacitor to any external circuitry. Three possible geometries of a supercapacitor are shown in Figure 5.1. Layers may be stacked in a parallel-plate structure, placed side by side in a co-planar geometry, or even formed axially.

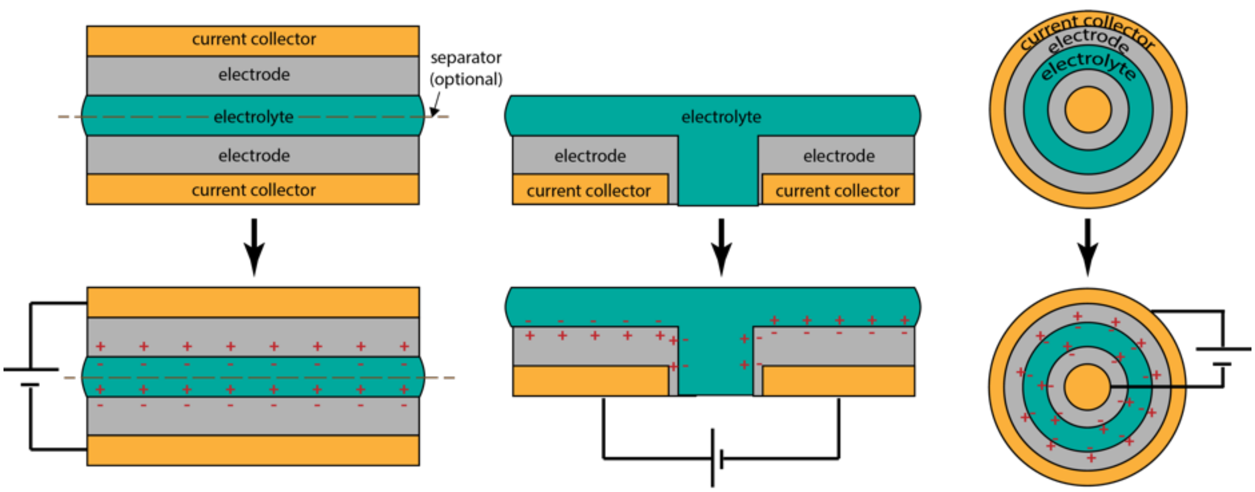


Figure 5.1: Left: parallel-plate supercapacitor geometry. Middle: co-planar supercapacitor geometry. Right: axial supercapacitor geometry. When a voltage is applied, charge layers build up at the interfaces between the electrodes and electrolyte.

When a voltage is applied between the two electrodes, ions within the electrolyte migrate towards the two electrode interfaces, causing the buildup of opposing electrostatic charge layers at each interface. As seen in Figure 5.1, the number of charge layers is double that of a standard capacitor, contributing to the "super" capacitance of a supercapacitor. Unlike the charging and discharging processes of batteries, which utilize semi-irreversible reactions that involve ions moving across layer boundaries and changing the chemistry of those layers, the charging and discharging processes of supercapacitors are completely reversible and do not involve chemical reactions. Thus, supercapacitors can theoretically be charged and discharged a limitless number of times. Even though they are generally capable of storing less energy than batteries and tend not to be suitable for applications requiring continuous operation over long periods of time, commercial supercapacitors have very high power density for their size due to the porous nature and high specific surface area of the electrodes. In addition, they can both charge quickly and supply large amounts of current quickly, unlike batteries. Commercial supercapacitors are commonly available in coin cell or cylindrical form factors and can be surface-mounted onto printed circuit boards. They are used today in numerous applications, such as power storage and delivery for regenerative braking, back-up power for static random-access memory (SRAM), and electric grid stabilization [288, 263]. As I shall discuss, *Vims* can find somewhat unconventional but invaluable uses as short-term power sources (lasting for a few days or less) for many small electronics such as piezoelectric buzzers, LEDs, Inertial Measurement Units (IMUs), and low-power microcontrollers.

Given these principles, I next present material selection considerations for designing *Vims*.

5.4 Materials

5.4.1 Layer Requirements

There exists an overwhelming number of candidates for each layer of a supercapacitor that materials scientists and chemists have developed to optimize particular aspects of a supercapacitor's performance. The materials comprising the highest performance supercapacitors today are often nano-engineered materials and require fairly complex synthesis in an advanced chemistry lab or cleanroom [268]. In this section, I distill the key properties of each layer that are needed to successfully make a functional supercapacitor and apply them to commercially available, cheap, and household-safe (mostly edible) materials to make *Vims*.

5.4.1.1 Current collector

The important features of a good current collector are high conductivity, mechanical flexibility, and, to some extent, low cost. Edible gold leaf is a widely available ingredient that fits these criteria. As cheaper alternatives, I also explored carbon-based options, such as rolled graphite foil, which yields equally good results. Although less costly than gold leaf, I found that edible silver leaf serves as a poor current collector, perhaps due to surface oxidation that results in high contact resistance with electrodes.

5.4.1.2 Electrode

A supercapacitor's storage capacity is largely a function of the surface area of the interfaces between the electrodes and electrolyte. As such, the electrode material should be conductive but, unlike a current collector, porous. Activated charcoal is an obvious choice for *Vims*, as it is one of the most successful materials even in conventional supercapacitors [301] and is also obtainable in a cheap and edible form. Activated charcoal has many household uses and is available as a loose powder, in edible capsules as a dietary supplement, and in pouches as air or water filtration material. It can even be made at home: wood or other organic matter may be burned to make charcoal, which can in turn be "activated" by adding calcium chloride, bleach, or lemon juice.

5.4.1.3 Binder

A binder is used to turn the electrode and electrolyte base materials into forms that can be printed or spread. The binder should be an agent that can be dissolved in water or another environmentally friendly solvent to create a viscous paste or gel that does not have large clumps. Good candidates are additives used to thicken liquids or doughs in cooking or baking, such as eggs, carboxylmethyl cellulose (CMC), and cornstarch.

5.4.1.4 Electrolyte

An electrolyte is an ionic liquid or gel that allows for the migration and distribution of electrolyte salts and can be spread onto the electrodes without completely dissolving them. Commercial supercapacitors often use lithium salts, but *Vims* should use an electrolyte comprising non-toxic salts, such as sodium chloride (NaCl, or table salt), calcium chloride, and/or potassium iodide, dispersed in a gel. The simplest way to make an electrolyte is by dissolving salt in a polar medium, such as water, and adding a binder, such as one described previously, as a thickener. Although water is one of the cheapest and most abundant solvents, one drawback of water-based electrolytes is that the maximum voltage that can be applied between two electrodes should be capped to ∼1.5V to avoid the hydrolysis of the water in the electrolyte (i.e. the permanent breakdown of water molecules into hydrogen and oxygen gases) [356]. *Vims* may be chained in series to overcome this voltage limitation. Still, *Vims* made with water-based electrolytes also need to be encapsulated to prevent evaporation, which otherwise causes a *Vim* to become non-functional in ∼1 week, depending on environmental conditions. Although possessing lower salt solubility than water, glycerin, a food-grade ingredient that is also a plasticizer, is a good alternative that allows for higher working voltages and also does not dry out over time.

5.4.1.5 Separator

If the electrolyte used is thin in consistency, a separator between electrodes is needed to prevent inadvertent electrical shorts. This separator should be electrically insulating but thin and permeable to allow the ions in the electrolyte to migrate across it. Paper is a low-cost and widely available candidate, though edible options such as rice paper or seaweed [357] can also be used. If the electrolyte used is thick or viscous enough to prevent the electrodes from touching, a separator is not needed at all.

5.4.2 Selecting Materials

In practice, when crafting *Vims*, designers may pick and choose different materials based on considerations such as their local availability, ease of storage and handling, cost, aesthetics, and even culinary factors. For example, edible gold foil may be desirable from an aesthetics standpoint or may be necessary when making edible *Vims*. However, it is costly, and its delicate nature makes it difficult to handle. Graphite is an easy-to-handle, less expensive alternative that is equally effective as a current collector. Table 5.1 offers a list of some material candidates for each layer that I tested, along with details that might help determine their desirability in different locations or for applications. The materials I use for the exemplar *Vim* recipe, described and characterized in the rest of this chapter, are highlighted in bold. Of course, performance is also a noteworthy facet, though I found that several materials, such as CMC and guar gum, can be used interchangeably when layer thickness is normalized. Figure 5.2 depicts some of the specific ingredients I used. All materials listed are non-toxic (many of them edible), can be made flexible and thin to allow them to conform to arbitrary surfaces, and can be shaped by hand or hand tools.

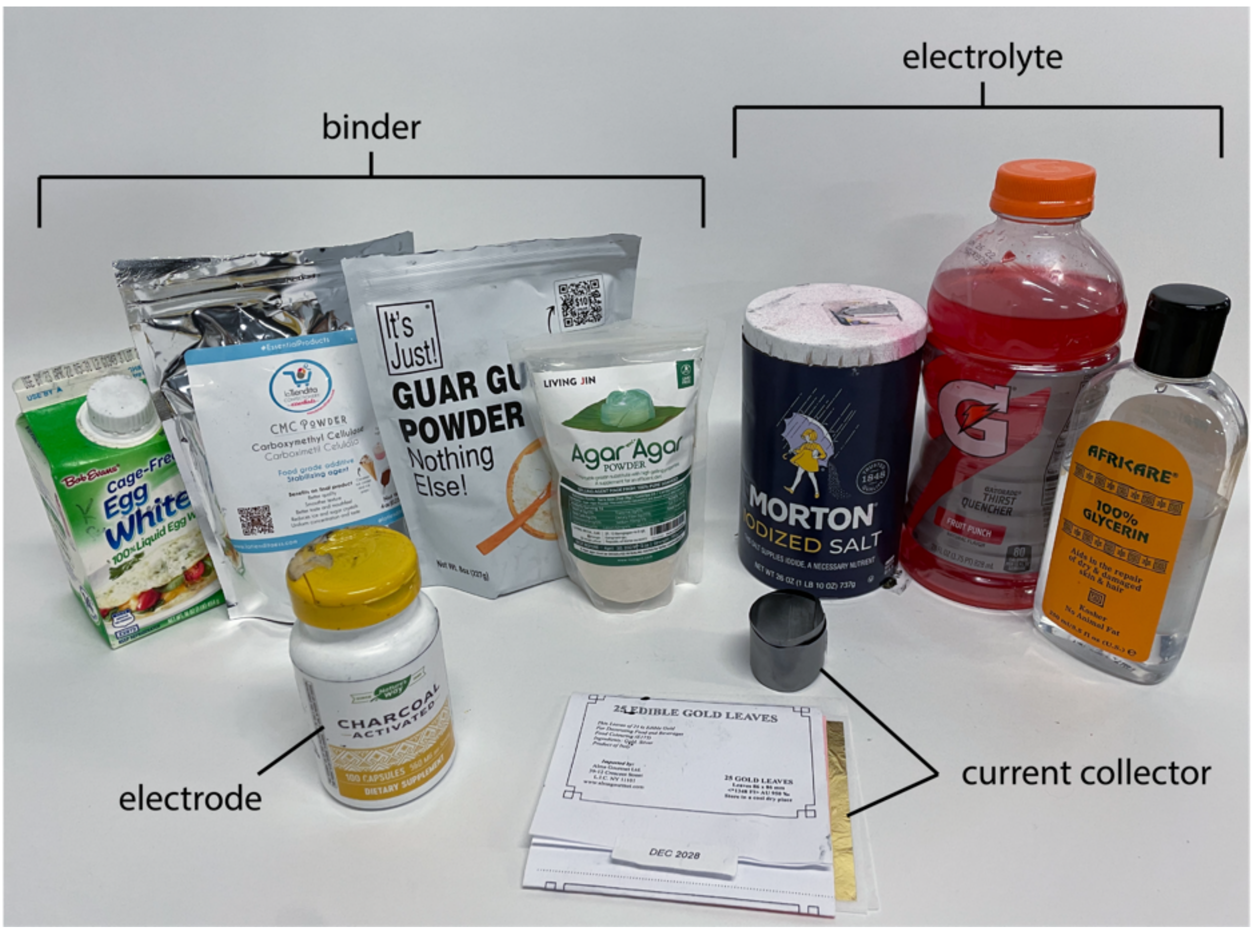


Figure 5.2: A selection of ingredients that can be used for making *Vims*. Back row, left to right: egg whites, carboxylmethyl cellulose (CMC) powder, guar gum, and agar agar (binders); table salt, sports drink, and glycerin (electrolyte ingredients). Front row, left to right: activated charcoal supplement pills (for electrode), edible gold leaves (current collector), roll of graphite (current collector).

In the rest of this chapter, I operationalize the principles outlined thus far and detail the fabrication, characterization, and applications of the most successful *Vim* recipe.

Table 5.1: *Vim* Material Candidates and Selection Considerations

Layer	Material	Availability	Cost	Form & handling	Aesthetics	Culinary factors	Performance
Current collector	Gold leaf	Online retailers, specialty culinary stores, art stores	4¢/cm^2 ($50/g)	Delicate sheets. Needs careful handling w/ tweezers, needs to be mounted to a substrate.	Associated w/ luxury. Shiny, gold-colored	Tasteless. Used as edible decoration.	Good – comparable to graphite
	Graphite	Online retailers, potentially homemade	0.5¢/cm^2 (19¢/g)	Sheets or rolls. Can be cut w/ hand tools or laser/vinyl cutter	"Industrial" steel look. Gray	Not conventionally consumed.	Good (baseline)
Electrode	**Activated charcoal**	Online retailers, pharmacies, home improvement stores, potentially homemade	2¢/g	Powder or granules. Can stain clothing	Black, opaque	Tasteless. Used as additive for color in breads & pasta	Good (industry standard)
Binder	**CMC**	Online retailers, specialty culinary stores	4¢/g	Powder. Shelf-stable. Results in spreadable gel.	Milky-colored	Tasteless. Used as thickener.	Good (baseline). Stable over months.
	Guar gum	Online retailers, specialty culinary stores	1¢/g	Powder. Shelf-stable. Results in spreadable gel.	Milky-colored	Tasteless. Used as thickener.	Good. Stable over months. Comparable to CMC.
	Chitosan	Online retailers, potentially homemade	7¢/g	Powder. Needs to be dissolved in vinegar. Shelf-stable. Results in spreadable gel.	Mostly clear with yellow hue	Not vegetarian. Has slight odor.	Stable over months. Slightly lower power density than CMC.
	Agar agar	Online retailers, specialty culinary stores	3¢/g	Powder. Needs to be warmed to spread. Warps as it dries.	Clear with brown hue	Tasteless. Used as thickener & in jellies	~1 week shelf life due to warping
	Gelatin	Most grocery stores, online retailers	2¢/g	Powder. Needs to be warmed to spread. Warps as it dries.	Clear	Not vegetarian. Tasteless. Used as thickener & in jellies	~1 week shelf life due to warping
	Egg whites	Grocery stores, farms	1¢/g	Liquid or powder. Perishable. Coagulates when heated.	Mostly clear	Not vegetarian. Common food.	~1 week shelf life due to warping
Electrolyte (solvent)	Water	Grocery stores, nature	<0.1¢/g	Liquid. Evaporates over time. May squeeze out during assembly.	Clear	Tasteless	1.5V max per cell. ~1 week shelf life due to evaporation.
	Glycerin	Online retailers, grocery stores, pharmacies, specialty culinary stores	0.7¢/g	Thick liquid w/ oily consistency. Doesn't dry out. Flammable >200°C.	Clear	Sweet. Used as thickener/sweetener	Good (baseline). Stable over months.
Electrolyte	Cheese	Grocery stores, potentially homemade	1¢/g & up	Solid blocks. Perishable. Needs to be cut or melted to spread or shape. Warps as it dries.	Opaque, white, yellow, or orange. Waxy.	Common food. Has odor.	Lower power density. ~1 week shelf life due to drying/warping.
	Table salt	Grocery stores, nature	0.7¢/g	Granular. Can take time to dissolve depending on solvent.	Colorless	Common ingredient in many dishes	Good (baseline)
	Sunscreen	Online retailers, grocery stores, pharmacies	5¢/g	Gel or liquid. Dries over time.	White	Not edible	~1 week shelf life due to evaporation
	Sports drink	Online retailers, grocery stores, pharmacies	0.5¢/g	Powder or pre-mixed in water. Requires encapsulation to prevent squeeze-out	Varies in color, depending on drink	Salty, sweet. Often consumed w/ flavor additives.	Lower power density if dissolved in water
Separator	Paper	Online retailers, office supply stores	0.3¢/g	Sheets. Can be cut w/ hand tools or laser/vinyl cutter	Varies	Not conventionally consumed	Only needed if electrolyte is runny
	Seaweed	Online retailers, specialty culinary stores, harvested	10¢/g	Sheets. Can be cut w/ hand tools.	Dark green, "leafy"	Salty, umami taste. Common in Asian cuisines.	Only needed if electrolyte is runny

5.4.3 Exemplar *Vim*

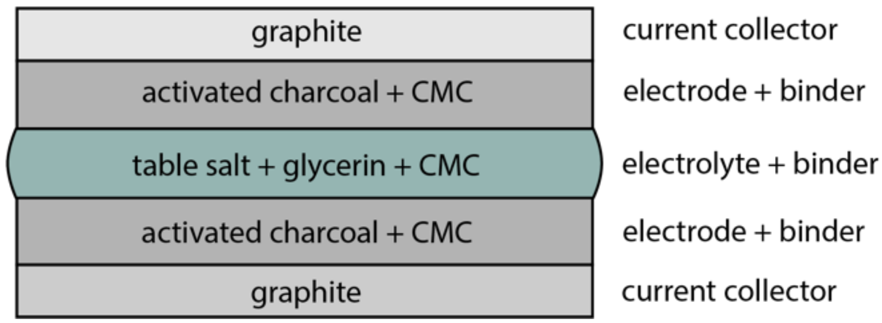


Figure 5.3: The stack-up for the exemplar *Vims*.

The stack-up for the exemplar *Vim* is shown in Figure 5.3. I utilize rolled foils of 127µm-thick graphite, a naturally occurring form of carbon that can be used as plant food, as the current collector and substrate. Graphite is cheap, abundant, conductive, and available in flexible sheets that function as both a substrate and a current collector. As in commercial supercapacitors, I use activated charcoal as the electrode. I extract powdered activated charcoal from dietary supplement capsules. I select CMC as the binder, as it forms electrode and electrolyte inks that are spreadable (unlike less viscous choices like sports drinks) and odor-free (unlike other choices like eggs, cheese, or chitosan). CMC is a cellulose gum that is a common thickener and emulsifier used in ice cream, biscuits, and candy. It also yields the highest performance *Vims* by a small margin when compared to guar gum and chitosan. For the electrolyte, I mix table salt with glycerin and CMC. The cost of materials to make a *Vim* of the size shown in Figure 5.4 ($\sim$11cm^2) is approximately \$0.13 (USD), with \$0.12 of that being the cost of graphite.

5.5 Fabrication

The fabrication process for making *Vims* is straightforward and can be conducted in a standard makerspace. I fabricate *Vims* by hand, but I note below where steps may be automated to facilitate higher throughput. The most time-consuming steps are preparing the electrode and electrolyte inks – up to 5 hours, largely due to the slow dissolution of salt in glycerin. However, these inks may be prepared in large batches and kept in sealed containers with no special storage requirements, allowing ad hoc fabrication to take only 10 minutes.

5.5.1 Electrode

First, the electrode and electrolyte inks are prepared. For the electrode (<10 minutes total if not pre-prepared), activated charcoal and CMC are mixed in a 20:1 weight ratio (w/w) and dissolved in water (1:6 activated charcoal:water w/w). I wish to use as much activated charcoal as possible to maintain conductivity; just enough water is added to create a spreadable ink, and just enough CMC is added for gelling (to prevent the electrode from simply returning to a loose powder form upon drying). Glycerin is added as a plasticizer to prevent cracking during drying in a 10:1 activated charcoal:glycerin weight ratio. The ink is stirred for 5 minutes. CMC may be swapped for other binders listed in Table 5.1 without modification to this step.

5.5.2 Electrolyte

Next, the electrolyte is prepared (4.5 hours total if not pre-prepared). Table salt is added to glycerin at a ratio of 80g table salt:1kg glycerin. A good electrolyte has an abundance of mobile ions, so I choose this concentration because it is roughly the solubility of NaCl in glycerin at room temperature. To speed up dissolution, the solution is stirred at 800rpm on a temperature-controlled hotplate at 120°C for 4 hours or until the salt is completely dissolved. Glycerin's flash point is 199°C and can safely be heated to temperatures lower than this.[4] Water can also be added to facilitate the dissolution of salt, but as previously noted, the presence of water limits the working voltage of the resulting *Vims* [356] so must be evaporated subsequently. CMC is then added as a thickener at a weight ratio of 1:5 CMC:glycerin solution, and the mixture is stirred by hand and left to gel and homogenize for 30 minutes. The resulting electrolyte is thick enough to hold its shape but still spreadable with a rod or stick. When using water instead of glycerin, more binder is needed to achieve the proper viscosity (1:2 binder:water).

5.5.3 Assembly

The next step is to form the electrode on the current collector (∼5 minutes). The electrode mixture is screen-printed onto the graphite current collector, which also serves as a substrate (Figure 5.4). It is then left to dry on a hotplate at 120°C for 5 minutes. This is repeated to make a second electrode. After screen-printing, the electrodes are ∼150µm thick. Screen-printing is a common technique for forming thin ink layers. It can be performed by hand, as I do here, with a screen and squeegee, but it also can be done on industrial machines for mass production. Alternatively, the electrode ink may be deposited by a 2D plotter with a syringe attachment (similar to the method described in [2]). If ultra-thin gold foils are being used instead of graphite, they must first be mounted to a substrate for mechanical stability. There are no electrical requirements for substrate materials; one may use separator materials as listed in Table 5.1 or any other material that has desirable mechanical properties for the target application. Gold foil may be mounted to a substrate by simply wetting the substrate with water or egg and using tweezers to gently drop the foil onto the surface.

[4] https://www.sigmaaldrich.com/US/pt/sds/sigma/g2025

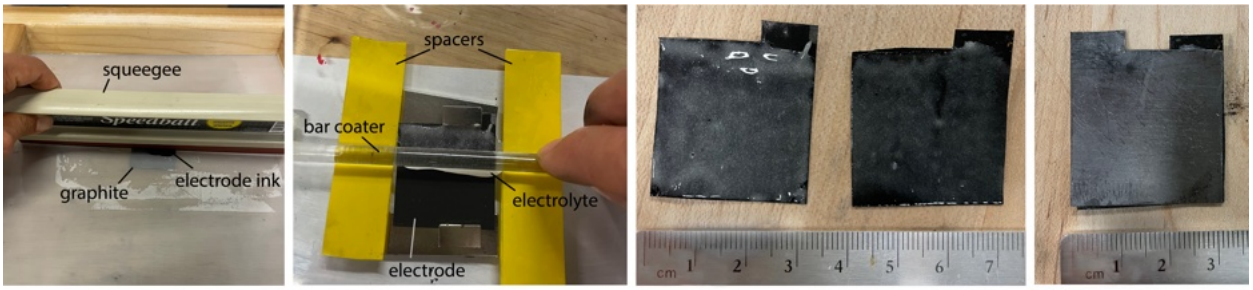


Figure 5.4: Fabrication of *Vims*. 1. Electrode ink is screen-printed onto pre-cut current collectors. 2. After drying, electrolyte gel is spread onto the electrode-coated current collectors via blade-coating. 3. This is repeated on another current collector to get 2 *Vim* halves. 4. After drying, the 2 halves are pressed together, with the electrolyte sides facing one another.

The electrolyte layer is then formed on the electrodes (∼5 minutes). The electrolyte ink is applied to the dried electrodes via blade-coating, an alternative to screen-printing that is more suitable for thick or gelatinous media (Figure 5.4). Blade-coating is a simple technique that is commonly performed by a machine for the industrial-scale manufacturing of organic electronics, but it can also be done by hand, as I do here, with a glass rod and spacers that define the layer height. Two spacers are made from layers of electrical tape that are stacked until they are each 400µm thick. An electrode is placed between the spacers. A generous amount of electrolyte is then applied to one side of the electrode between the spacers, and a glass rod is pressed on the spacers and then drawn across the area of the electrode to evenly spread the electrolyte. The samples are again dried on a hotplate at 120°C for 5 minutes. If using a water-based electrolyte instead of a glycerin-based one, the drying step is skipped to prevent complete evaporation of the electrolyte.

Finally, the two *Vim* halves are pressed together, with the newly dried electrolyte sides facing one another. Once dried, the electrolyte I use is flexible but firm. It holds its shape when pressed and does not squeeze out, so a separator is not necessary. If using a less viscous electrolyte without any binder, such as a sports drink, a separator should be placed in between the two halves to prevent electrical shorting. The separator also acts to absorb some liquid electrolyte and prevent it from completely squeezing out during assembly.

5.5.4 Customizing Geometry

Depending on the application, it may be more aesthetically favorable to make co-planar *Vims* that expose the color of the electrodes (see Figure 5.1). For co-planar *Vims*, fabrication is complete after the application of the electrolytes — no sandwiching is needed. The fabrication procedure that I have described is not readily extendable to the axial configuration of Figure 5.1, but because all layers are thin and conformable, parallel-plate *Vims* may be rolled into a cylinder if such a geometry is desired. Additionally, *Vims* may be bent, cut, or torn

Figure 5.5: Readily fabricated in a makerspace with hand tools, *Vims* can take a variety of shapes and form factors.

into arbitrary shapes. Examples of a few basic geometric and aesthetic variations are shown in Figure 5.5. Such modifications may even be made after *Vims* are initially fabricated and tested, so they may be easily adapted with minimal material waste as a prototyper iterates upon their design.

5.6 Characterization

5.6.1 Electrical Characteristics

Supercapacitors can be electrically characterized by a multitude of metrics, such as energy density, capacitance, equivalent series resistance (ESR), and temperature dependence. Here, I offer a subset of measurements that I believe are most applicable from the perspective of a designer who needs to decide if *Vims* can provide sufficient energy to power a given direct current (DC) application. Namely, I present (1) charging characteristics: voltage and current vs. time under constant-voltage and constant-current charging schemes; and (2) discharging characteristics: voltage on a *Vim* vs. time (a) under no load (i.e. self-discharge) and (b) under different current loads.

5.6.1.1 Charging Characteristics

One benefit of supercapacitors in comparison to batteries is that they may be safely and very quickly charged to full capacity – on the order of seconds, in the case of commercial supercapacitors. Because fires and other permanent damage from over-heating are not concerns, *Vims* may be charged with practically no limit on charging current. Figure 5.6 shows the charging current vs. time of a *Vim* 11cm^2 in area charged to 2V under a constant-voltage charging scheme. The *Vim* reaches >1.9V within 5 minutes. I consider it "fully" charged when the charging current drops below 1mA, which occurs after 9 minutes.

Vims may be more quickly charged by using a constant-current charging scheme with higher current. Under a charging current of 100mA, a *Vim* reaches 2V in 5 seconds. Thanks

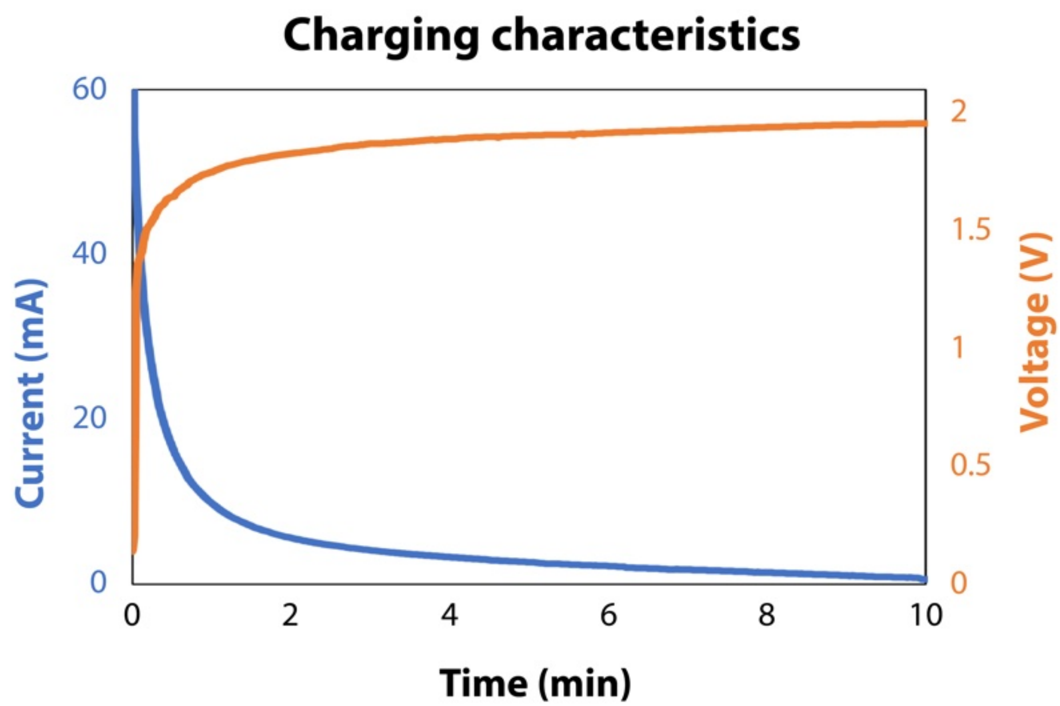


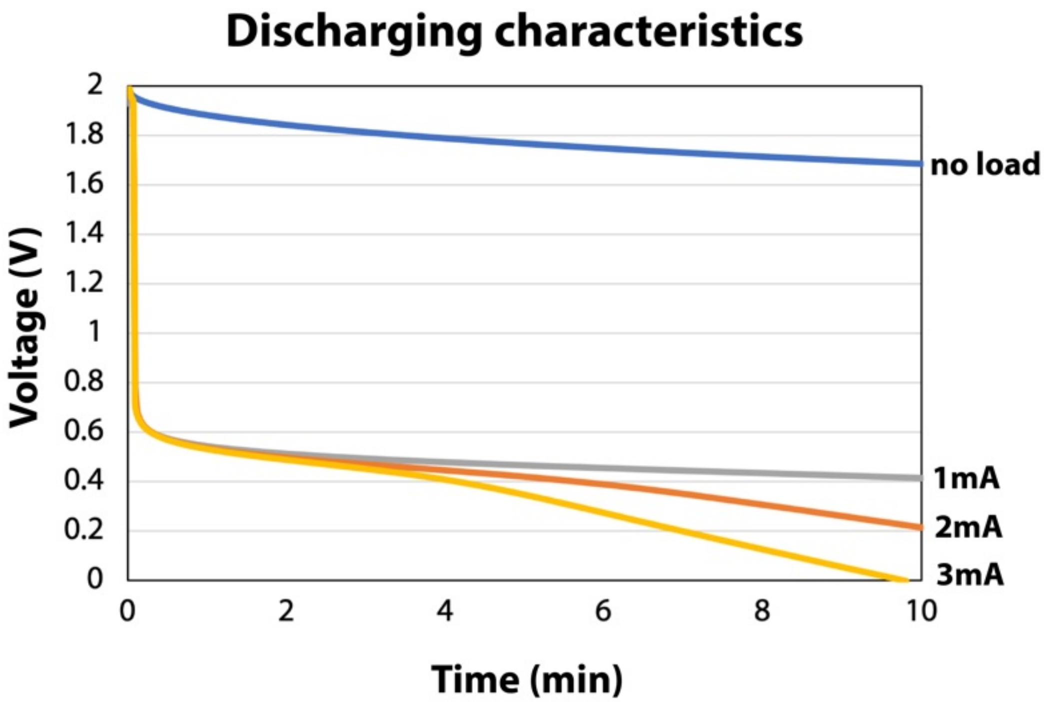
Figure 5.6: *Vim* current (left y-axis) and voltage (right y-axis) under constant-voltage charging to 2V. Design is 11cm^2 in area.

to their flexibility to charge under varying current, *Vims* can also be directly connected to solar panels or other energy harvesters without the need for a charge regulator.

5.6.1.2 Discharging Characteristics

Unlike batteries, the voltage that a supercapacitor holds drops over time, both with and without a connected load. This makes the customary metric of amp-hours for estimating battery life a poor one for estimating *Vim* life. Figure 5.7 shows discharge characteristics of a single *Vim* (11cm^2 in area) under different loads. Prior to each trial, the *Vim* is charged to 2V for 10 minutes. For these tests, I use a standard DC power supply plugged into a wall outlet for charging. When no load is applied, the *Vim* slowly discharges due to a leakage current of ~40µA through the *Vim* itself (measured as the steady-state current when the *Vim* is fully charged), with the voltage discharge rate decreasing as the absolute voltage drops. After 2 hours, the *Vim* has ~1V remaining, and 24 hours later, the *Vim* has ~0.5V.

The bottom plot in Figure 5.7 also shows the voltage discharge rate of the *Vim* under different loads, measured after 8 minutes of loading; this metric can be used to roughly estimate the total operational time of a *Vim* for a given application – assuming a constant current load, the expected operational time is simply the tolerable voltage drop of the application divided by the *Vim*'s voltage discharge rate. However, in reality, the actual time



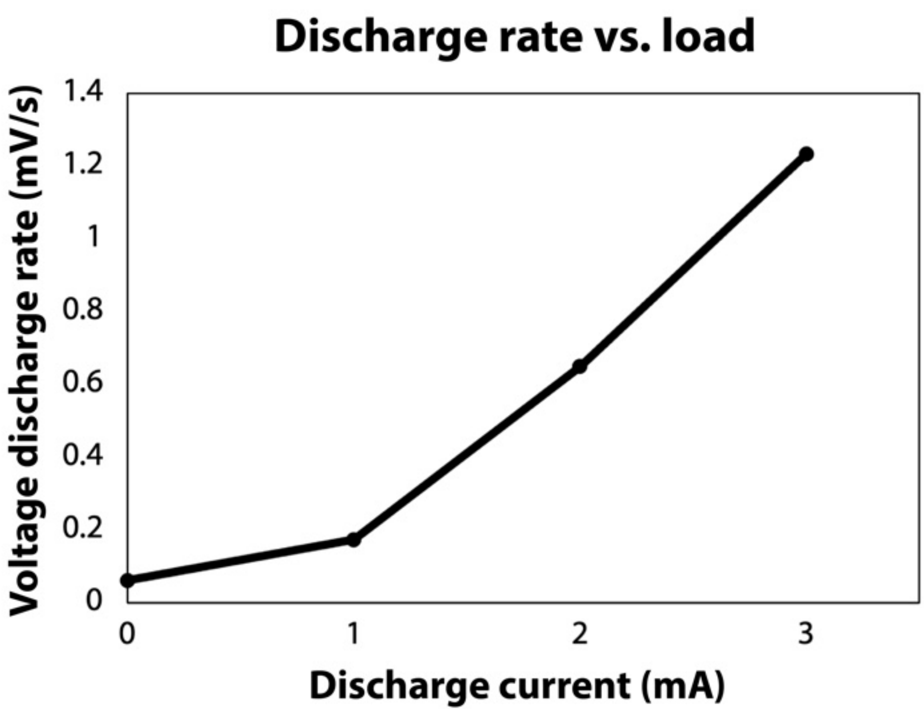


Figure 5.7: Top: voltage vs. time under different constant current load conditions. Bottom: Discharge rate (linear estimate at the 8 min mark) vs. current loading. Design is 11cm^2 in area.

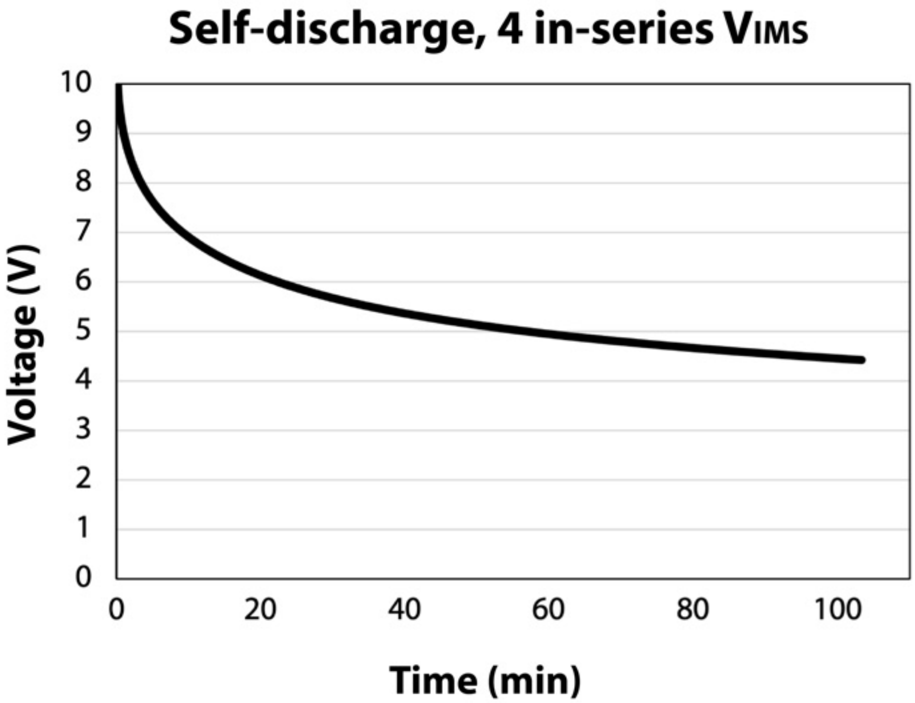


Figure 5.8: Self-discharge characteristics of a chain of 4 *Vims* connected in series and charged to 10V for 3 minutes.

a *Vim* can last under a given load is more complicated. First, although voltage is expected to drop linearly under a constant current load, due to stray resistances and capacitances, it is not in fact linear. Most notably, as can be seen in the top plot of Figure 5.7, there is a large initial drop in voltage when a DC current load is applied. This is due to the DC internal resistance (DCIR) of the *Vim*, which is a combination of the resistances within each layer and the contact resistances between layers. For commercial supercapacitors, this is generally less than 10Ω. For *Vims*, this value is much higher and is estimated to be ∼500Ω (calculated from the 2mA discharge curve on the left plot in Figure 5.7 as the initial voltage drop divided by the load current). This results in an instantaneous ∼1.5V drop. While *Vims*' high DCIR is a limitation, it can somewhat be overcome by chaining *Vims* in series, thus summing together their voltages (see Figure 5.8). With just 4-5 small *Vims*, we can reasonably unlock many possible applications that require common input voltages such as 3.3V or 5V.

In contrast to charging and discharging conventional batteries, charging and discharging *Vims* do not chemically change the composition of *Vims*, so they may be theoretically rapidly charged and discharged virtually endlessly without degradation in performance. I did not perform a detailed stress test, but I have charged and discharged individual *Vims* over at least 100 cycles across 3 months with no noticeable change in performance.

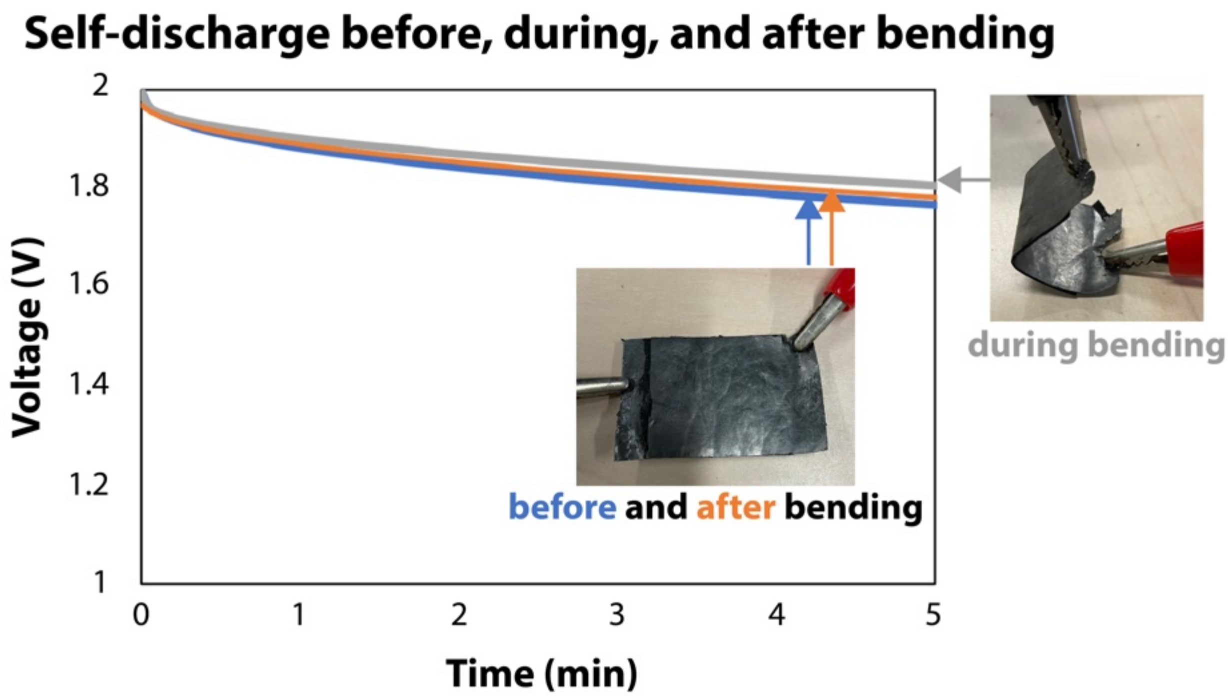


Figure 5.9: Voltage discharge curves for a *Vim* before bending to 90 degrees (red), during bending (gray), and after bending (blue). Leakage decreases during bending, and characteristics are recovered once the *Vim* is re-flattened.

5.6.2 Mechanical Robustness

As previously mentioned, *Vims* may be arbitrarily bent or rolled. As seen in Figure 5.9, when a *Vim* is bent to 90 degrees, its self-discharge curve actually improves slightly, exhibiting a very small 7% decrease in the discharge voltage vs. time slope. This may be attributed to the slightly increased surface area-to-thickness ratio, and thus total capacitance ($C \propto A/t$), during bending. When unbent, the *Vim*'s original characteristics are restored.

Vims may also be cut or reshaped after they are fabricated to make one or more *Vims* of different shapes. The resulting pieces are functional, with their energy storage capacity scaling with the new area of each piece. The exemplar *Vim* recipe additionally does not dry out or warp over time. Thus, *Vims* are stable for months when stored under ambient indoor conditions; subsequent testing of *Vims* 3 months after initial fabrication and testing yielded indistinguishable electrical characteristics. They remain mechanically flexible. Alternate *Vims* made with, for example, water-based electrolytes or cheese do dry, warp, and crack as liquid evaporates, rendering them non-functional within 1 week. To prolong working lifetime, those *Vims* may be sealed with a thin encapsulation material, such as melted beeswax or chitosan, which can be brushed onto a *Vim*. For applications that undergo bending, a flexible encapsulation material (i.e. chitosan instead of beeswax) should be selected.

5.6.3 Backyard Degradation

Even though *Vims* are reusable and rechargeable, they are also designed to be disposable and backyard-degradable in a very short period of time without specialized industrial conditions. In fact, the exemplar *Vims* may be beneficial additions for garden soil health. Activated charcoal and graphite are immediately usable as soil conditioner [155]. Glycerin is also known to be a degradable soil additive that can promote soil nutrient retention and healthy microbial growth [25]. CMC has been reported to decompose under normal environmental conditions within 14 days [81]. The example materials that I listed in Table 5.1 are similarly ones that are well known to be backyard-degradable.

As a sanity check, I buried a *Vim* in my yard to observe decomposition. I buried the *Vim* under 5 cm of soil in a sunny garden during the summer. The soil was alluvial soil (loose clay and silt) with a moisture content of 30% as measured by a handheld moisture meter at the beginning of the study. The *Vim* was dug up and photographed every 15 days and was also weighed starting from day 45 (see Figure 5.10). Over the course of 60 days, the *Vim* had visibly degraded, with almost everything between the graphite current collectors no longer present; the graphite pieces were mostly intact but had become very brittle, breaking into pieces when lifted from the soil. At days 0, 40, 60, and 90, visible pieces of *Vim* were unearthed and weighed to quantify mass decomposition. Only 30% of the *Vim*'s mass remained after 60 days. Plants near the burial site appeared to remain healthy. This is unsurprising, since I intentionally selected components that are known to be backyard-degradable.

Of course, decomposition times depend on environmental conditions, and they also vary based on *Vim* material selection. I buried a *Vim* with edible gold leaf electrodes in the same garden plot as the *Vim* with graphite electrodes. The gold leaf *Vim* lost 80% of its mass within 1 week. I hypothesize that this is in part due to the fact that the gold leaf is a mere 0.1µm in thickness compared to the 127µm thickness of the graphite foil.

5.7 Applications

I now present several use cases for *Vims*. The first leverages the customizability of *Vims* to enable new aesthetic and form factor flexibility when it comes to electronics prototyping and showcases energy storage as a first-class design element. The second and third leverage the decomposability of *Vims* to unlock novel interactive technologies that are in turn backyard-degradable in their entirety.

5.7.1 Electronics Prototyping

Because *Vims* can take on arbitrary shape and, to some extent, color and texture, they may be double as decorative design elements and power sources. For example, edible gold foil may simultaneously serve as a *Vim* current collector and as a material for creating a gilded

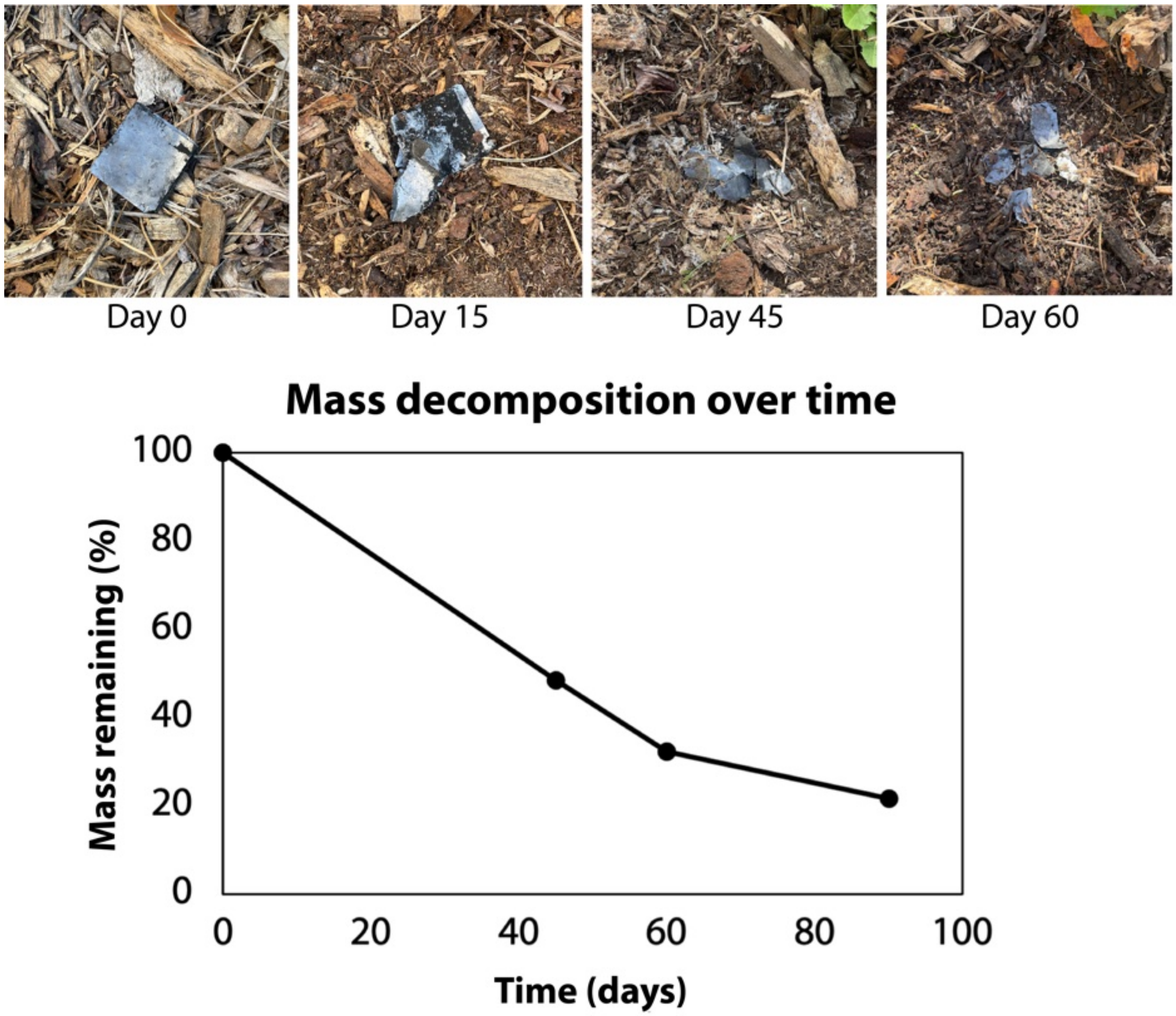


Figure 5.10: Top: series of images qualitatively showing *Vim* degradation across 60 days buried in backyard soil. Bottom: plot of mass of visible pieces (unearthed and measured at 40, 60, and 90 days) over time.

appearance. *Vims* built on this gold foil can be extremely thin and conformable, wrapping around otherwise awkward corners or curves of a design. Additionally, *Vims* eliminate the need for battery-related enclosures, such as spring clips or protective casings.

Figure 5.11 shows the before and after photos of a small digital clock with its coin cell battery replaced by 5 co-planar *Vims* in series, integrated into a decorative pattern on the body of the clock. The clock remains operational on a single 5 minute charge for over 2 hours. I also successfully powered a temperature sensor with a chain of 3 *Vims*. Other modules

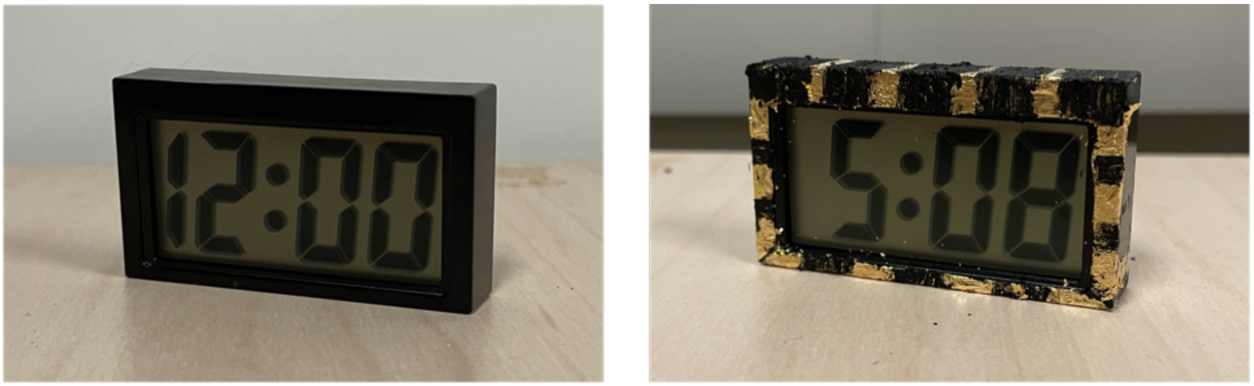


Figure 5.11: Left: a commercial digital clock powered on a coin cell battery. Right: clock with coin cell battery removed and powered by decorative *Vims* (5 co-planar units in series)

with specs well within *Vims*' operating regime include piezo buzzers [5], LEDs [6], vibration motors [7], and IMUs [8]. Series of 5 or fewer *Vims* can be expected to power such applications for minutes, hours, and potentially even days, depending on frequency of activation.

5.7.2 New Edible Experiences

As discussed in Chapter 4, human-food interaction has recently garnered great interest within the HCI community. It has been the subject of a Special Interest Group at CHI 2022 [62] as well as several workshops at CHI, CHI PLAY, and DIS [75]. By definition, eating is an experience that is ephemeral and thus potentially another domain for which *Vims* are ideal. An edible version of *Vims* opens the door for fully edible interactive systems that were not possible before, enabling new, sustainable interactions during the experience of eating that do not require external electronics, as Füpop and other previously reported systems for HFI do. The exemplar *Vim* design may be made fully edible by replacing the graphite current collectors with edible gold foil. This *Vim* variation on its own is relatively neutral in taste, which makes it a good candidate for emulating different tastes with current. The tongue can perceive microamps of current, with reported thresholds as low as 5µA [313]. Ranasinghe et al. created a "Digital Flavor Synthesizer" that, in conjunction with heating and cooling elements, used 20-180µA of current to simulate sour, spicy, and minty tastes [277, 276]. An edible *Vim* is capable of delivering these levels of current. Figure 5.12 plots the current of an edible *Vim* charged to 2V versus time when shorted through a 47kΩ resistor, which approximates the resistance of a human tongue. A future user study is needed to more accurately characterize how such *Vims* would taste, but based on characterizations

[5] e.g. Multicomp ABI-014-RC, available from Newark Electronics
[6] e.g. onsemi CAT3661, available from onsemi
[7] e.g. Vybronics motors, available from DigiKey
[8] e.g. Maxim MAX21100 IMU, available from Maxim Integrated

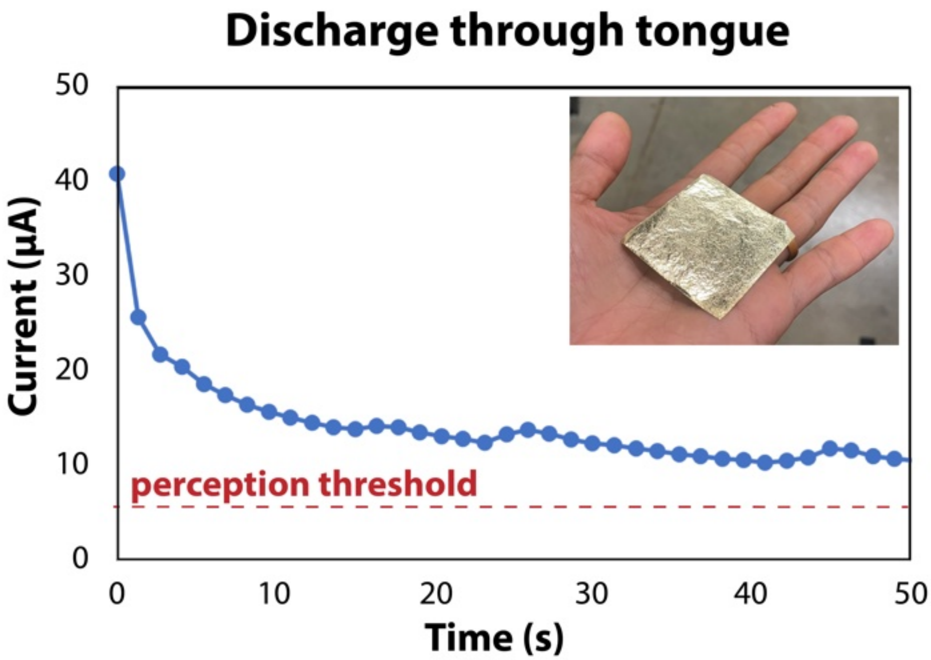


Figure 5.12: Current vs. time for a charged edible *Vim* shorted through a 47kOhm resistor, which approximates a human tongue. Inset: image of *Vim* tested.

from existing research, the delivered amounts of current may be perceived as mild salty or sour [276]. Edible *Vims* may be disguised as decorative gold flakes on a cake to deliver a tantalizing surprise to the eater. Alternatively, by using cheese as an electrolyte, the *Vim* may instead improve the taste of cheap cheese, emulating the taste of a much more expensive, aged cheese with subtle flavor notes. We might imagine yet other applications, such as augmenting or restoring eating experiences for people with taste dysfunction and powering digestible electronics for internal health monitoring. Edible *Vims* could also allow programmable flavors to supplement Augmented or Virtual Reality (AR/VR) experiences, triggering flavor profiling consistent with what a user sees and thinks they are eating.

5.7.3 100% Degradable Wearables

In addition to increasing the eco-friendliness of prototyping with conventional electronics, *Vims* present a major step towards making standalone backyard-degradable systems. *Vims* may be paired with *Lotio*, a backyard-degradable skin-worn display that is the subject of Chapter 6, to create a novel wearable that can be powered all day and then afterwards discarded in backyard soil, where it degrades within months.

Fashion is a domain that is fitting for fully backyard-degradable interactive interfaces.

Despite laudable ongoing efforts to shift away from the culture of "fast fashion," social pressures to continuously refresh wardrobes persist. Some accessories are only appropriate to don in certain occasional situations; it is still often considered a faux pas to re-wear outfits or accessories [279]; fads inevitably fall out of style. Thus, when it comes to smart wearables for accessorizing and personalizing a look, there is value in offering technology that is targeted for only a few hours' worth of wear and can then be disposed of in an environmentally responsible way.

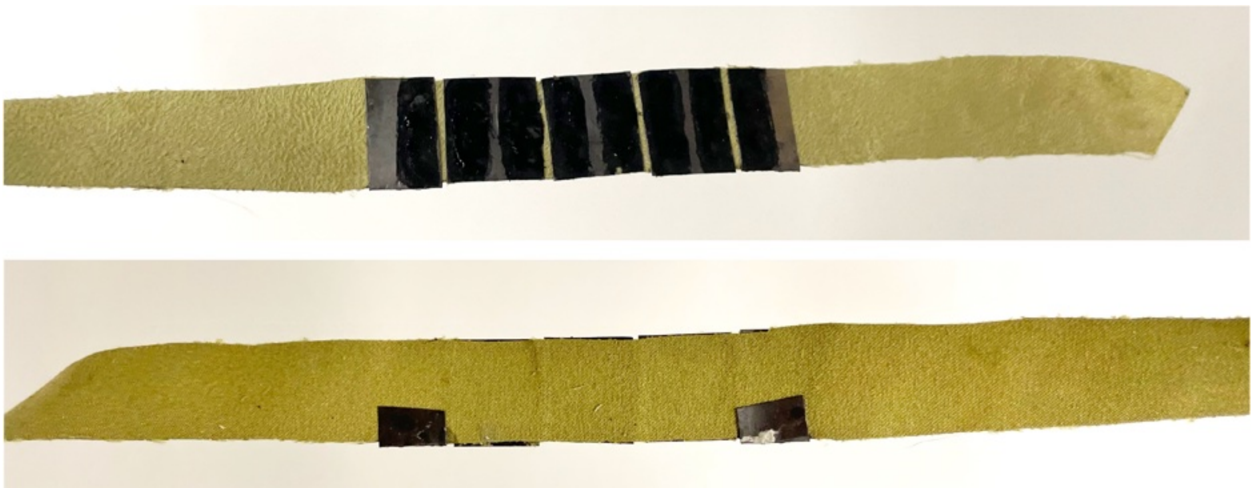


Figure 5.13: The front (top image) and back (bottom image) of a Vim "bracelet" for powering a 100% backyard-degradable wearable.

Coupled with other sustainable materials, *Vims* allow us to design electronic wearables that do not result in any landfill. Inspired by DuoSkin [147] and other on-skin interfaces [360, 204, 365], Figure 5.14 shows Lotio, a 100% backyard-degradable, 2-state on-skin display that I developed, powered by 4 co-planar *Vims* connected in series. The *Vims* are mounted on a cotton bracelet (see Figure 5.13) with pine resin, a natural sticky substance that can be used as an adhesive. The cotton used is a leftover strip from a sewing project and is dyed with chlorophyllin, a natural green pigment. Field studies have shown that cotton fabrics can fully degrade in soil under ambient temperatures (25-29°C) within 1-3 months [363, 228]. Other alternatives that are backyard-degradable include paper, untreated or naturally dyed hemp, lyocell, and linen (flax). The graphite current collectors at each end are wrapped around the back of the bracelet for contact to the electrodes of the display. Alternatively, if preferred, *Vims* may be adhered directly to the skin, either with a skin-safe, biodegradable adhesive or by mounting *Vims* onto surgical tape that can then be placed on the skin. *Vims* are thin and flexible enough to conform to and move with the skin, and when the latter strategy is used, the feeling is akin to wearing a fabric bandage. For a more luxurious aesthetic, gold current collectors may be used instead of graphite ones. A bracelet comprising 4 *Vims* in series holds more than enough charge to power multiple state changes for this wearable over

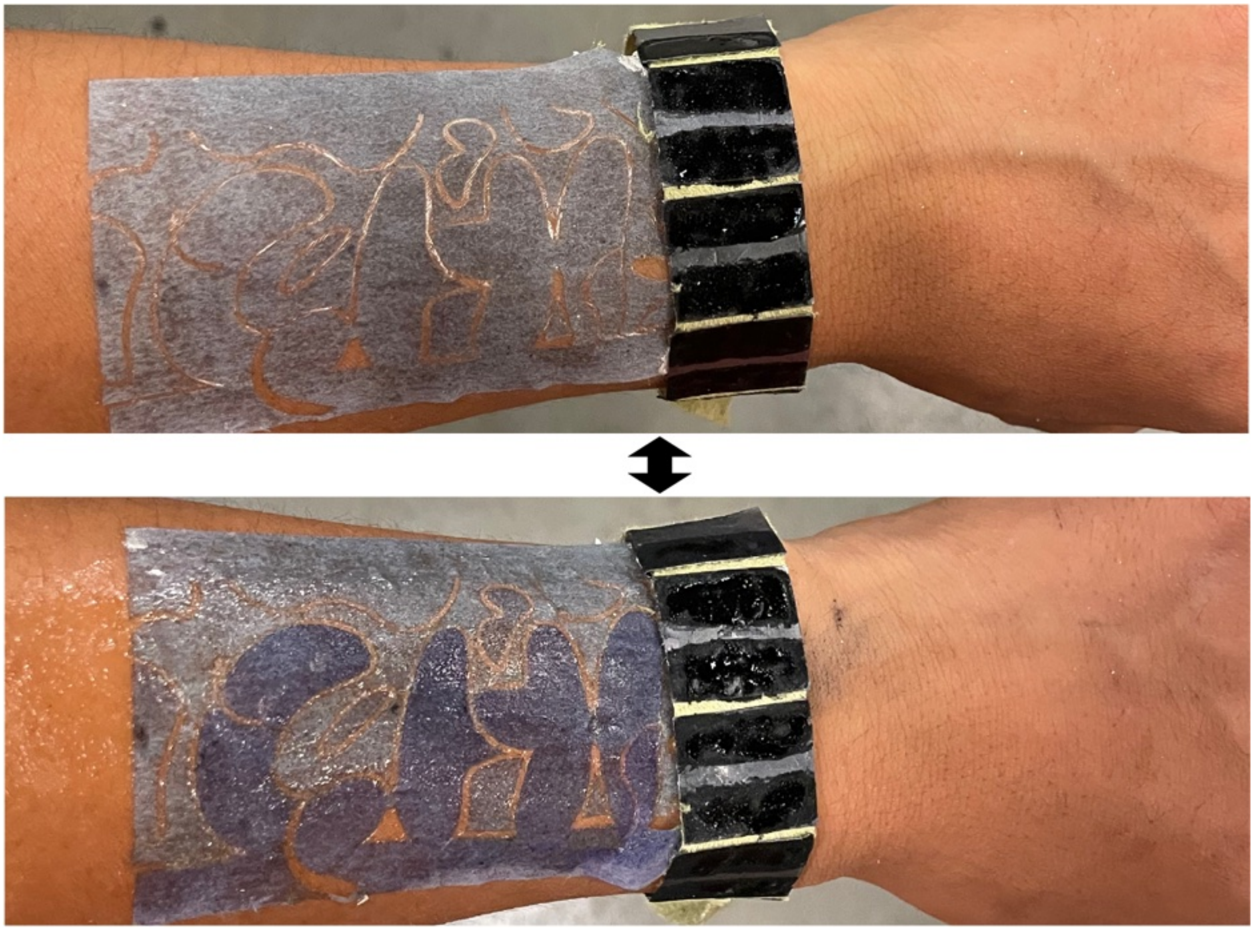


Figure 5.14: A *Vims* bracelet can power the switching between two states of Lotio, a backyard-degradable skin-worn display that will be described in Chapter 6, for an entire day. A hidden message (here, "CHI") may be concealed or exposed.

the course of a whole day. Chapter 6 will present the technical details of how Lotio itself works and also more details about the *Vims*-powered Lotio wearable.

5.8 Discussion and Future Work

5.8.1 Democratizing Energy Storage Design

A key advantage of *Vims* with respect to existing work is their ability to be safely fabricated at home with commercially available, non-toxic materials. While I believe that this is the first demonstration of backyard-degradable supercapacitors made with DIY-friendly techniques, modern DIY communities of non-expert makers and technologists have been thriving for over a century [175]. The HCI literature has seen numerous demonstrations of DIY assistive technologies [124, 223], biology [84], e-textiles [34, 36], cell phones [224], and home electronics [289]. Although they are more laborious than simply ordering pre-packaged, commercial goods, DIY approaches to fabrication, relying on cheap and widely available technologies such as screen- and inkjet-printing [176, 154], have been touted as democratizing technological engagement, empowering makers, fostering emotional attachment, and increasing engagement with nature, among other benefits [321, 124, 209, 91]. DIY material development in particular has also been shown to provide valuable opportunities for personal expression and experiential learning [283, 256, 21].

In more formal classroom and workshop settings, DIY making has been cited as an approach to help children develop an inclination to study Science, Technology, Engineering, and Math (STEM) [48, 206] and to engage new communities in technological design and prototyping [273, 302]. Requiring nothing more than what can be found in a classroom or makerspace, the design of *Vims* could be a valuable addition to an educational curriculum. Making *Vims* requires more effort than, say, ordering batteries online or pressing "START" on a digital fabrication machine, but *Vims* could be packaged as self-contained kits with pre-portioned quantities of materials to facilitate fabrication, allowing my design to be more widely adopted and understood. Other kinds of kits might contain large batches of pre-mixed electrode inks and electrolytes, allowing *Vims* to be fabricated in just a few minutes with minimal equipment. Such kits could be used in classrooms, hackathons, special events, or even just in personal settings, supporting budding electronicists' creative freedom, encouraging the blending of technology with art and craft [37], and also helping makers better understand the environmental costs of powering their systems.

The accessibility of *Vims* fabrication rests on the assumption that ingredients are locally available. While there may exist particular locations where this is not in fact the case (and where the aforementioned kits cannot be shipped to), the design of *Vims* is fortunately readily adaptable to different materials that might be more available or economical in different locales. For example, in locations where CMC is difficult or costly to obtain, eggs (e.g. on a farm with birds) or agar agar (e.g. by the sea) are suitable replacements with only minor performance differences. The materials I experimented with, listed in Table 5.1, make up just a small subset of options. In this way, I believe that *Vims* can be made by a wide range of populations and, when coupled with energy harvesting methods, can offer small-scale power solutions in remote environments and developing communities.

I see the large-scale efforts enabled by DIY culture as critical to inspiring new uses of sustainable materials and encouraging novel aesthetics for *Vims*. I have confidence that by following the basic design guidelines presented in this chapter, motivated makers can find success with many different materials for *Vims* that I have not explored, maybe even discovering and publishing their own variants and related artifacts, as has been the case for hardware kits [36]. Open-source libraries of natural materials, such as *materiom*[275], could further help facilitate the discovery of new material combinations. Future workshops could test these claims and reveal new insights, designs, and breakthroughs that I could never discover alone.

Still, DIY-friendly approaches are not without concerns when it comes to sustainability.

It is possible that excessively lowering barriers to fabrication could lead to an overzealous fabrication of goods instead of practicing reuse and repair [209]. Furthermore, while I believe that DIY-friendly approaches can accelerate discovery of novel, better *Vims*, I understand the value of enabling the eventual large-scale production of sustainable designs, which could start as DIY approaches, to truly maximize both technical capabilities and public awareness of related environmental issues. It may be fruitful to guide explorations of new materials and aesthetics for *Vims* with techniques that are adaptable to higher-throughput technologies, such as inkjet-printing or roll-to-roll manufacturing.

5.8.2 Selecting the Most Sustainable System Design

In the Related Work section of this chapter (Section 5.2), I noted that there are several promising approaches that use non-backyard-degradable materials and electronics to create systems that can sustain themselves virtually forever without batteries. Furthermore, high-capacity batteries based on lead acid or lithium ion, while containing toxic components, can last for long stretches of time, and some would argue that batteries will only become more eco-friendly as industries focus increasingly on recycling technology [133]. So how might one choose *which* "sustainable" power scheme to use for a given portable design? Factors to consider include the duration and frequency of an interaction, voltage and current needs, local availability of materials, and availability and capability of energy sources, such as wireless chargers, RF sources, solar power, or body heat, among others. For many applications, *Vims* are in fact not the most desirable option, both in terms of performance and in terms of overall environmental impact. For example, for applications that require operation over long periods of time, relying on *Vims* would likely be inconvenient, as they discharge relatively quickly and would thus have to be re-charged frequently. For high-power applications, non-backyard-degradable conventional batteries might instead be a wiser – or sometimes the only – choice. For certain microwatt-scale applications in environments where there are reliable RF networks, ambient backscatter communication, possibly in conjunction with energy harvesting, could be the most fitting solution.

Vims are ideal options for interactions that only occur once or over a short period of time, or happen where no wireless energy transfer is available. Like ambient RF, *Vims* are more than capable of providing the voltage and current needed to power piezo buzzers. Furthermore, *Vims* can provide minutes of power for many interactions that require more than 1mW of power, such as resistive heating, LED driving, micro-motor actuation, or positional sensing with an IMU. Such applications demand more instantaneous power than current energy harvesting technologies are capable of delivering. Hobbyists have even modified Arduino microcontrollers to run on 3.3V and <10µA of current [166], which *Vims* could easily sustain for hours and potentially days. Additional opportunities include any designs that might benefit from *Vims*' fast and fuss-free charging. For such applications, the *Vims* design approach can offer a more eco-friendly solution than what currently exists. As I have described, fashion and food are two domains that are ripe with opportunities. Other potential scenarios include powering temporary environmental sensors in remote environments or powering transient electronics that may be dangerous if obtained by hostile parties. Applications will only grow in number and scope as work in ultra-low-power systems continues to burgeon [280].

As future work, I hope to integrate *Vims* with backyard-degradable energy generation or harvesting solutions to further broaden the realm of backyard-degradable interactive systems. *Vims* as presented can already be charged with commercial solar cells, but to enable more systems that can be responsibly disposed of in their entirety, it is a logical next step to explore the viability of more eco-friendly energy harvesting solutions to continuously power a system without the need for periodic recharging. Electrogenic organisms that generate electricity could be one avenue of exploration [199, 47]. Admittedly, this will be a challenging undertaking, as even energy harvesters engineered with non-sustainable materials generally generate less than 1mW of power.

5.8.3 Limitations

Despite their potential, it is indeed difficult to imagine *Vims* replacing conventional batteries or existing power storage in many – perhaps even most – applications in the near future. Even when it comes to temporary wearables, edible technology, and other domains for which I believe *Vims* are well suited, there remains much work to be done to better understand and overcome limitations. Systematic user studies are needed to better understand how *Vims* might feel on the skin across different populations, what other kinds of substrates they might be applied to, and how robust they are to various activities and environments. Additionally, *Vims* are durable enough to be stored unsealed in an indoor environment and can operate in the presence of small amounts of moisture, but being inherently backyard-degradable, they are susceptible to prolonged exposure to elements such as rain, sweat, and saliva, limiting their lifetime. In some cases, solutions may be straightforward. For example, encapsulating *Vims* with materials such as beeswax or chitosan can mitigate the effect of moisture (encapsulation can also be a strategy for prolonging the working lifetime of *Vims* made with water-based electrolytes, which otherwise evaporate). Still, large amounts of moisture will ultimately degrade a *Vim*'s performance by potentially dissolving critical layers or otherwise hastening degradation. *Vims* in their current state are thus not appropriate for wet or underwater situations. Future experimentation may uncover more water-resistant material sets, but it is likely that such materials would also be less easily backyard-degradable, which may be a competing design consideration.

Moreover, designing within the limitations of "safe" workflows and degradable materials comes with performance tradeoffs. *Vims* are inherently low capacity and low performance relative to commercially available supercapacitors. Increasing storage capacity and decreasing self-discharge likely requires more advanced material engineering. For example, capacitance scales with electrode area, so nanoscale texturing would be advantageous. Another major performance limitation of *Vims*, as noted previously in the Characterization section, is a high DCIR, which causes a large initial drop in voltage when a *Vim* is connected to a load. To decrease the contact resistance between layers, and therefore lessen the voltage drop, layers should be deposited in succession in a vacuum or inert gas environment, and inks should be ultra-homogenized such that constituent particles are extremely small (<0.1µm). Finally, chemists today have remarkable abilities to concoct specialized materials with just the right combination of desirable properties, and these materials unsurprisingly lend themselves to much higher-performance supercapacitors than the results of a DIY "scavenging" approach. Still, I do believe that there is great potential for *Vims* to improve in performance beyond what I have presented by encouraging broader communities to simply try more material combinations and different fabrication techniques. Furthermore, even with their current capabilities, many applications – ones that are low power, operate on the order of 1 day, and can can handily be powered by *Vims* with their current capabilities. As discussed in the previous sub-section, *Vims* can be used for the rapid prototyping of low-power electronics and wearables, for sustainable electronics education, and for edible electronics. For these designs and many others beyond what I alone can imagine, switching to *Vims* can generate new degrees of both design flexibility and environmental friendliness.

5.9 Conclusion

Designers of battery-powered electronics like our friend Alice from the Introduction often resort to adjusting their designs at the last minute to accommodate batteries that are too large, too rigid, or too long lasting relative to the intended designs. This chapter presents *Vims* – fully backyard-degradable supercapacitors that are capable of powering small applications for over one day on mere minutes of charge time. Instead of searching for and waiting for her lithium ion battery to arrive after finishing initial prototyping, Alice could have incorporated a flexible, gold *Vims* chain as an aesthetic feature of her ring design, iterating simultaneously upon all elements of the design in concert with one another instead of waiting until the end of the design process to search for an energy storage solution. Furthermore, the backyard-degradability of *Vims* might have inspired Alice to choose backyard-degradable alternatives for other elements of her design as well, allowing her entire system to be used as compost for her garden after her event. *Vims* are well suited as an alternative to batteries for many interactions and systems that are relatively low power and ephemeral or temporary in nature. *Vims* not only provide a key missing piece needed for standalone backyard-degradable interactive systems; they are also easily fabricated at home with a variety of different materials, opening new doors in design customization, sustainable materials development, and green electronics education. This is just the beginning for what I hope is a new relationship between designers and power.

Chapter 6

Lotio: A Lotion-Mediated, Skin-Worn Display

In the previous chapter, I detailed the development of *Vims*, a backyard-degradable electrical energy storage module that is a critical component for virtually all standalone backyard-degradable interactive electronics. Moving forward, of course, it is also important to develop a selection of backyard-degradable electrical components that *Vims* and other future backyard-degradable energy sources can power, such as actuators, sensors, and eventually microprocessors. In this chapter, I present the design and development of one such backyard-degradable component to add to the growing toolbox – a display [1]. I demonstrate an example of how forcing ourselves to work within the constrains of backyard-degradable materials is a constructive practice that encourages us to consider new affordances of materials and novel interaction schemes.

In particular, drawing inspiration from the emerging genre of skin-based electronics, I leverage the natural uses of lotions and propose them as mediators for driving novel, low-power, quasi-bistable, and backyard-degradable electrochromic displays on the skin and other surfaces. I detail the design, fabrication, and evaluation of one such "Lotion Interface," named *Lotio*. I discuss how Lotio can be customized using low-cost, backyard-degradable everyday materials and technologies to trigger various visual and temporal effects — some lasting up to fifteen minutes when unpowered. I characterize different fabrication techniques and lotions to demonstrate various visual effects on a variety of skin types and tones. I highlight the safety of *Lotio*'s design for humans and the environment. Finally, I report findings from an exploratory user study and present a range of compelling applications for Lotion Interfaces that expand the on-skin and surface interaction landscapes to include the familiar and often habitual practice of applying lotion.

[1] Large portions of this chapter have previously appeared in the 2023 ACM CHI proceedings. The original citation is as follows. Katherine Wei Song, Christine Dierk, Szu Ting Tung, and Eric Paulos. 2023. Lotio: Lotion-Mediated Interaction with an Electronic Skin-Worn Display. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, Article 854, 1–15 [306].

6.1 Introduction

As discussed in Chapter 5, fashion and wearables comprise a domain that is well suited for backyard-degradable systems. Despite efforts to combat fast fashion, people still refresh their wardrobes frequently. Often, it is not seen as socially acceptable to re-wear outfits and accessories worn for special events. Thus, in addition to trying to change the way people think about fashion, when developing electronic wearables, "smart clothing," or skin-worn technologies, it may be fruitful to develop technologies that are designed to fit the timescales with which people accessorize their body – that is, ones that can degrade or be disposed of in an environmentally responsible way after only a few hours' or days' worth of wear.

Recent advances in materials and fabrication methods have enabled the creation of a wide range of skin-worn technologies. These interfaces provide new methods of always-available input [364], biomedical sensing [343], personal expression [205, 145], and beyond. Almost without exception, these systems are wired to external electronics that control and power the on-skin interactions. Working within the constraints of backyard-degradability forces us to consider alternative schemes, particularly ones that are low power and also can operate without microcontrollers. In this chapter, I propose leveraging the intrinsic electrical properties of lotion, along with its related human habits, as a mediator between the wearer and skin-based technologies to build limited-state but functional backyard-degradable systems. Such lotion-mediated interfaces enable new forms of embodied interaction [179], simultaneously lending the wearer control over when skin-worn technologies are active and augmenting the perhaps mundane act of applying lotion, imbuing it with additional meaning, functionality, or playful opportunities.

Lotions and creams exist in nearly all cultures throughout the world, dating back to around 23,000 BC [60]. While they are used in various applications today, such as surface cleaning, textile restoration, plumbing, and food, one of the most well-known uses for them is on the skin. There, they serve a variety of purposes including personal care, medicine delivery, beautification, and protection from the elements. Although their capabilities as an electronically active material are not the subject of focus for their intended use cases, almost all lotions are electrolytes, utilizing salts as ingredients and possessing mobile ions that I believed could make them potential replacement for commercial electrolytes in devices such as capacitors and, as I will discuss, electrochromic displays. Furthermore, lotions and creams and by design safe and "backyard-degradable," seamlessly blending into the body once applied and becoming indistinct from the wearer. The act of applying lotion is familiar, often habitual, and laden with cultural meaning. One's past experiences inform a mental model of lotion as a transformative agent, able to alter the properties of the skin. This mental model is constructed via perception [138]: makeups and tanning lotions alter the aesthetic appearance; moisturizers and exfoliants alter the texture; sunscreen reduces susceptibility to UV exposure; hydrocortisone causes an itch to subside. Although knowledge around the body is tacit, humans have a rich implicit understanding of how lotions affect their skin. To this end, I introduce the concept of Lotion Interfaces: a novel interaction paradigm for on-skin or on-surface technologies.

6.1.1 Lotion Interfaces

Lotion Interfaces are interfaces that sense and respond to lotion. While Lotion Interfaces do not *have* to be skin-worn – a possibility I return to later in the Discussion – I use on-skin applications for illustration throughout much of this chapter, as the skin is arguably one of the most cross-culturally relatable sites for lotions and also the site of a rich body of work in Human-Computer Interaction (HCI). The on-skin interaction model is described as follows:

(a) The user wears skin-worn technology. This technology may take the form of a wearable sticker, makeup, henna, a temporary tattoo, or a traditional tattoo, among others.

(b) The user applies lotion over the skin-worn technology. While a diverse range of lotions, creams, and gels can be used, the lotion must be perceptible to the Lotion Interface, either through electrical or chemical properties.

(c) The skin-worn technology senses the lotion and enacts some transformation. Transformations may be visual (e.g., color, shape), tactile (e.g., texture), or digital (e.g., setting an alarm, changing the mode of a connected wearable device).

(d) The lotion is absorbed, evaporated, or removed. The designer may allow the transformation to persist beyond the act of applying lotion itself.

Lotion Interfaces may provide positive feedback to the user when lotion is applied through the form of playful aesthetic experiences, reinforcing healthy skin routines. They might also provide an opportunity to give the user additional control over an otherwise overwhelming swarm of electronic communications, activating notifications only during the few windows in a day that a lotion or cream is applied. Lotion Interface design takes inspiration from themes of cosmetic computing [67], beauty technology [342], hybrid body craft [144], and ubiquitous computing [368]. Building upon the idea of touch as an aesthetic experience [114, 180], Lotion Interfaces enable intimate interactions with technology that have different and/or expanded social and personal connotations compared to existing touch-based interactions.

6.1.2 Leveraging Semantic Priming and Mental Models

In addition to leveraging existing mental models, Lotion Interfaces enable semantic priming [222]. In cognitive psychology, priming is a phenomenon in which exposure to an initial stimulus affects the user's response to a following stimulus. Semantic priming occurs when the two stimuli are semantically similar, increasing the accuracy or speed of responses to the subsequent stimulus. There are countless opportunities to leverage semantic priming when designing interactive interfaces, especially skin-worn technologies that can be applied or modified during self-care routines. For Lotion Interfaces in particular, the initial stimulus is the act of applying lotion, accompanied by tacit knowledge and past experiences. When a user applies a medicinal cream or ointment, they are intrinsically thinking about their health. When applying makeups, users are primed towards aesthetics. The subsequent stimulus is the transformation enacted by the Lotion Interface. Semantically linking these two stimuli can enable more meaningful interactions with and more intuitive interpretations of skin-worn technologies – for instance, displaying UV exposure data when sunscreen is applied or communicating body temperature in response to an antibiotic ointment. Furthermore, displaying health data on the skin can lend a corporeality to the data, making it more salient to the user [24].

In this chapter, I position backyard-degradable Lotion Interfaces as a novel interaction paradigm for on-surface technologies, focusing particularly on skin-based electronics. As an exemplar Lotion Interface, I design and fabricate Lotio: a lotion-reactive, computationally-controllable electrochromic display that uses resistive sensing to detect the application of lotion and touch. I have taken care to use lotions and creams that are commonly used in many cultures throughout the world and have been deliberate in designing a skin-worn display that is visible on varying skin tones. Lotio represents just one of many possible embodiments of Lotion Interfaces. Aside from contributing the technical design of a backyard-degradable electronic component, the design, fabrication, and evaluation of Lotio serves as an initial exploration of the broad design space of Lotion Interfaces (see Figure 6.1).

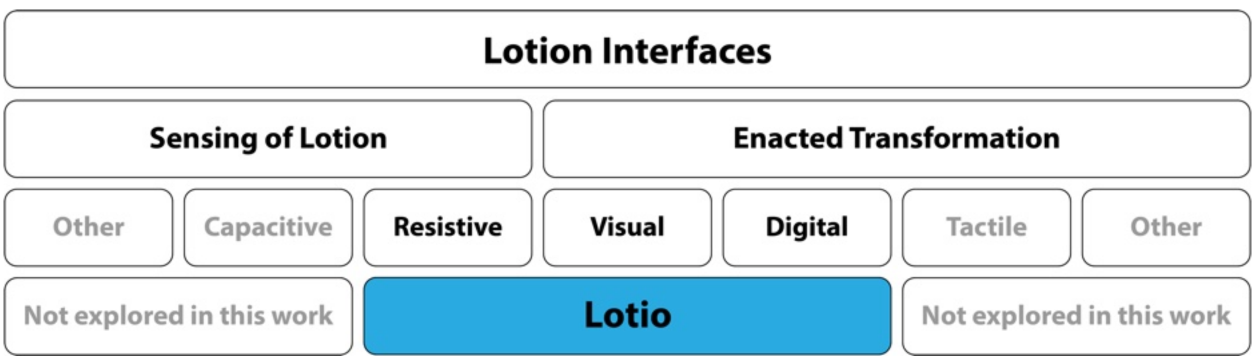


Figure 6.1: A subsection of the Lotion Interfaces design space illustrating how Lotio, my exemplar system, is situated.

6.2 Related Work

Recent research in HCI has shown that the skin provides a unique substrate for wearable electronics [146, 205, 217, 248, 361, 364, 366]. These technologies are inspired and enabled by materials research into epidermal electronics [109, 160]. Prior work has explored wearable technology in the form of silicone overlays [361, 364, 371], temporary tattoos [146, 205, 366], and electronic bandages [217]. Some of these interfaces have sensing capabilities, and others have built-in displays; however, many on-skin interfaces explore both input and display.

6.2.1 Input

Prior work has explored capacitive sensing [146, 205, 361, 364, 366, 371, 248], resistive sensing [205, 364], bend sensing with strain gauges [205, 366], and embedded sensors [217]. These techniques equip the user with new forms of always available input and enable novel types of body engagement such as posture sensing [205] and wound monitoring [217]. Lotion Interfaces expand this landscape. Because lotion can be sensed and identified using capacitive or resistive sensing, existing technologies that use these techniques can easily be adapted to support lotion-mediated interaction. As I will discuss subsequently, Lotio, an exemplar Lotion Interface, uses resistive sensing to distinguish between applications of lotion and touch events both with and without lotion.

6.2.2 Output

Prior work explored LEDs [205, 217], thermochromic pigments [146, 361, 145], and electroluminescent (EL) displays [366, 371] on the skin. LEDs and EL displays are emissive with fast response rates; thermochromic displays are non-emissive and change more gradually. These display types have different power requirements and are suited for different applications. There are even skin-worn displays that chemically react and change color in response to specific chemicals or UV exposure [143, 214], consuming no power at all. Although displays of this type are only capable of conveying a narrow amount of information and are not computationally controllable, they have been cited as potentially useful designs for mediating the wearer's relationship with the natural environment. Together, these works showcase a compelling design space for on-skin displays. For Lotio, the application of lotion completes the circuit in an on-skin electrochromic interface, mediating both its input and output functionalities. The interface itself is simply a layer of electrochromic ink. Non-emissive with a variable response rate, this material complements the existing design space. A key distinction over other skin-worn displays is the low-power nature of the material. Although EL displays (such as those used in [366, 371]) draw low-current, they require high voltage. Thermochromic displays (such as those used in [145]) rely on resistive heating, which inherently draws relatively large amounts of current. Lotio consumes 0-350µW, can be driven at 1V and less than 1mA, and exhibits quasi-bistability. Unlike displays that rely on chemical reactions with particular environmental agents, Lotio is readily compatible with wearables or any device that can supply 1V, and it can be computationally controlled to display more rich information.

Preceding skin-worn interfaces in the field of HCI, Epidermal Electronics originated in the field of Materials Science [160]. Functionally, Lotion Interfaces share similarities with epidermal sensors that monitor skin hydration [122, 173, 45, 123, 387] because such sensors could also detect the presence of lotion. However, while Lotion Interfaces might draw technical inspiration from such sensors, they are conceptually more than just sensors. Although Lotion Interfaces need to reliably sense the presence of lotion, it is not necessarily important that a Lotion Interface be an accurate hydration sensor because the individual already knows that a lotion is "hydrated" when they are applying it. Instead, Lotion Interfaces combine more basic lotion detection with some kind of appealing transformation, ideally without complex or power-intensive electronics. Lotio combines sensing and display with very little external circuitry required. Lotio uses poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) as an active electrochromic material. PEDOT:PSS has been used for epidermal electrochromic displays in the fields of Materials Science and Chemical Engineering [257, 41, 266], but existing approaches rely on specialized materials, techniques, and devices, such as carbon nanotube thin-film transistors [41]. I expand existing epidermal electrochromic electronics with a Do-It-Yourself (DIY) methodology and a new interaction paradigm in which readily-available lotions mediate the functionality of the interface.

Lotion Interfaces are yet another evolution in the wearable landscape as interactions and materiality transition towards lotions, creams, and topical skin gels. This new physicality enables a broader range of potential interactions. While applying lotion is usually done with fingers or hands, it is an intimate act that is aesthetically distinct from tapping a screen, stroking a fabric, or even existing touch interactions with skin-worn interfaces. This opens doors for both new opportunities and new considerations.

6.3 Design Considerations for Lotion Interfaces

Continuing to draw on related work as well as personal experiences with lotion and designing wearable devices, in this section I outline several design considerations for Lotion Interfaces.

As the diversity and popularity of Lotion Interfaces grow, we might imagine scenarios in the future in which the primary purpose of applying some lotions becomes activating a Lotion Interface. However, as a first step, I propose that we work within the existing paradigm of how lotions and creams are currently applied when designing Lotion Interfaces. Namely, lotions and creams are transient and infrequent interactions, they are absorbed into the skin, they exist as many different types with different functions, and they are used by people around the world with different skin types. I briefly describe these and their implications for Lotion Interface design here.

6.3.1 Transient and Infrequent Interactions

Unlike many other interactive materials, lotion is transient in nature —it absorbs and evaporates. Existing on-skin technologies are also arguably temporary, but whereas a temporary tattoo or makeup may last a few hours or days, lotion vanishes on the scale of a few seconds to minutes. Interactions with Lotion Interfaces should preserve and even embrace the essence of this unique ephemerality, which can create magical [5] or suspenseful [177] experiences. Designers of Lotion Interfaces should also take special care when considering the desired frequency of interactions. While a user might feasibly interact with a smartwatch, or even a touch-based on-skin interface, dozens of times within a single hour, it is much less likely for that user to apply lotion at a similar frequency. Lotion Interfaces should cater to

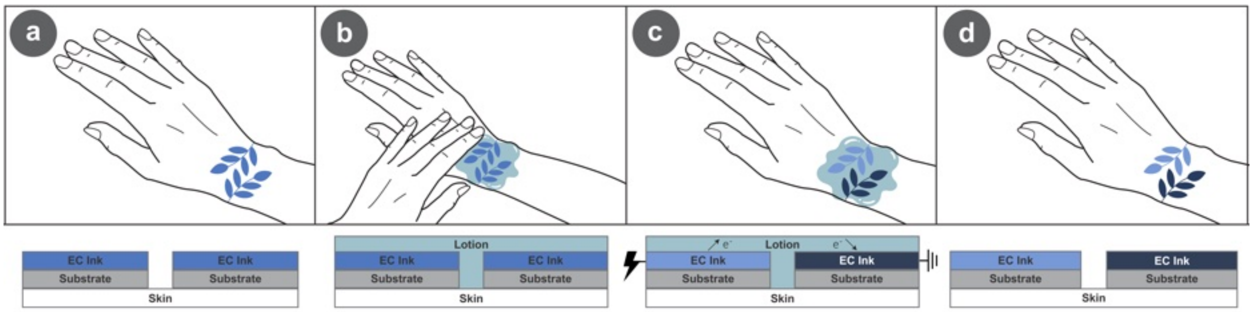


Figure 6.2: Interaction model for Lotio; chemical and material architecture is shown below the stages of interaction. a) Lotio functions as a static display in the dormant state, similar to a traditional temporary tattoo. b) Lotion is applied. c) The lotion behaves as an electrolyte, allowing electrons to move between portions of the design. One portion of the design is oxidized and becomes lighter in appearance; the other is reduced and becomes darker. d) The lotion is absorbed. The new coloring is maintained for some time even after power has been removed.

interactions that are infrequent in nature, ideally differentiating between always-available functionality and functions that are available only temporarily after lotion is applied. This might be embodied as having no functionality at all until lotion is applied, or alternatively, there may be multiple input modalities: infrequent lotion-mediated interaction in addition to conventional unmediated touch input [205, 146, 366].

6.3.2 Absorption

Lotions are formulated to be backyard-degradable – specifically, easily absorbable by the skin, which is a universal characteristic that is intrinsically linked to function and also gives lotion its transient nature, as previously discussed. This property should be preserved to avoid forced, unnatural interactions with lotion. This places constraints on the physical materials used when designing Lotion Interfaces. While Lotion Interfaces can take many different forms, the substrate should be thin and breathable to allow applied lotion to still be absorbed into the skin. Traditional permanent tattoos [343], powders [143], and bandages [217] enable lotion absorption through the interface. On the other hand, temporary tattoos [205, 248, 366], metal leaf [146], and silicone [149, 362, 361, 364, 371] are often moisture barriers and thus hinder this characteristic of lotion usage. However, these substrates may be micro-perforated to enable absorption. Other materials used must also be thin or permeable enough to not impede lotion absorption.

6.3.3 Multiple Lotion Types

Designers of Lotion Interfaces should enable semantic priming by tying functionality to lotion type. This can be achieved through designing a Lotion Interface with limited functionality that only responds to a single type of lotion: for instance, a UV monitor that reacts to sunscreen. Alternatively, this can be achieved through designing a more complex Lotion Interface with multiple functionalities enacted through differing lotion types.

Heading to her sister's birthday brunch, Selam applies foundation over her face-worn Lotion Interface. Sensing the applied makeup, the interface causes her lips to redden and her cheeks to blush [145, 143]. Later, Selam begins to feel a tingling on her upper lip and fears a cold sore may be coming on. She swiftly applies a topical cold sore remedy. Sensing the applied medication, Selam's face-worn Lotion Interface begins monitoring her skin for biomarkers of infection [260, 385].

6.3.4 Accounting for Skin Diversity

Lotion Interfaces must be inclusive, taking into account the full range of skin types and color tones. Skin-worn displays must be visible on a range of skin tones. Changes in texture [149] must be compatible on a variety of skin types [20]. Furthermore, Lotion Interfaces should account for cultural considerations in lotion type. Wherever possible, designers should use lotions and creams that are universally available, or allow interfaces to be tailored for individual use.

6.4 Lotio: An Exemplar Lotion Interface

Figure 6.3: Lotio sense and react to applied lotion. Left: "Ocean Waves" ring prototype behaves as a fashionable form of personal expression. Right: "Skyscraper Skyline" prototype extends the display capabilities of a smartwatch onto the skin.

To operationalize these recommendations, I designed and fabricated Lotio as an exemplar Lotion Interface. Lotio is a dynamic overlay worn on the skin that resembles a temporary tattoo (See Figures 6.3 and 6.4). Lotio foregrounds the interactive potential of lotion and empowers the user with new interaction capabilities and forms of personal expression. While

Lotio in this dissertation is presented as an exemplar backyard-degradable display in the toolbox of components for standalone backyard-degradable systems, it may also be used in conjunction with conventional electronics for more advanced functionality as well. In the absence of lotion, Lotio behaves as an input device, able to detect touch events. When lotion is present, Lotio additionally functions as a computationally-controllable segmented display, changing color in response to voltage (See Figure 6.2). Lotio can also use resistive sensing to detect when lotion is applied and activate certain functionalities on a connected device. In addition, because each lotion has a different absorption time constant and detectable current signature during color changes, it is possible for Lotio to distinguish between the application of different kinds of lotion as well. Here, I present a use case scenario to illustrate the interaction capabilities of Lotio:

Julio is playing tennis with his neighbor. Feeling the sun beating down, he reaches for his sunscreen between matches. He liberally applies sunscreen, covering the Lotio overlay on his forearm that is connected to his smartwatch. This generates a small electrical signal that triggers an app on Julio's smartwatch to check UV exposure data (from sensors integrated into the smartwatch or from connected sensors elsewhere on the body). The smartwatch sends signals for the Lotio overlay to display a pulsating warning symbol on Julio's arm. Noticing that his UV exposure is high, Julio suggests they break for the day.

This interaction demonstrates how semantic priming can be used to sculpt meaningful and intuitive interactions with Lotio and Lotion Interfaces. As seen in Figure 6.1, which illustrates just a small subset of the Lotion Interfaces design space, Lotion Interfaces are capable of (1) sensing applied lotion and (2) enacting a transformation. Lotio senses applied lotion via resistive sensing on exposed electrodes, and it is capable of enacting both visual (e.g., color change) and digital transformations (e.g., changing the state of a connected device). Lotio is just one of many possible embodiments of Lotion Interfaces. For example, the transformation may instead be textural or may be perceivable only to the wearer. In the subsequent sections, I focus on the design, fabrication, and evaluation of Lotio. I return to a consideration of Lotion Interfaces more broadly later in the Discussion section.

6.4.1 Operating Principles

The architecture of Lotio when lotion is applied is similar to that of an electrochromic display. Electrochromic displays utilize an active electrochromic material that, under applied voltage, undergoes a reduction or oxidation reaction that causes it to change color [11, 135, 238]. Lotio relies on a voltage differential between disjoint portions of electrochromic ink that function as electrodes. At least one electrode is connected to ground and another to power. Applied lotion behaves as an electrolyte, allowing electrons to move from the positive electrodes to the negative. The portion of the design connected to the positive electrode is oxidized and becomes slightly lighter in appearance; the portion of the design connected to the negative electrode is reduced and becomes dramatically darker in appearance. Very little lotion – just enough to cover the electrodes and the gap(s) between them (<1µm thick layer) – is needed to induce this transformation. Lotio is low power, operating on a little as 1V and consuming

Figure 6.4: Lotio is a dynamic overlay worn on the skin. When lotion is applied, Lotio functions as a computationally-controllable segmented display, with some portions of the design becoming more saturated and darker in appearance, and other portions of the design becoming less saturated and lighter in appearance. From left to right: "Ocean Waves" prototype on a finger, "Geometric Bear" prototype on a leg, "Skyscraper Skyline" prototype on the wrist as an extension to existing wearables, and Cosmetic "Eyeliner" prototype. I take care to ensure that Lotio's visual transformations are visible and comfortable on different skin tones and on different parts of the body.

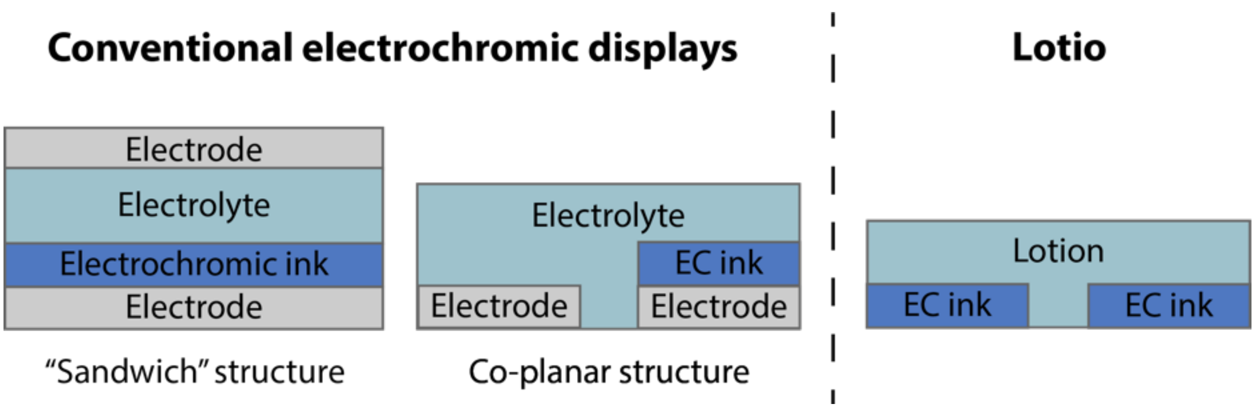


Figure 6.5: Two kinds of electrochromic display pixel geometries alongside Lotio's geometry. Left: sandwich structure. Center: co-planar structure. Right: Lotio. With lotion applied, Lotio most closely resembles the co-planar structure, but it uses the same electrochromic material for both the active layer and the electrodes.

tens of microamps while switching the display and during resistive touch sensing. This is considered physiologically safe [295]. It consumes no power when lotion is not present. Lotio is quasi-bistable, retaining its colored state after removal of voltage for tens of minutes.

Wearable electrochromic displays are in and of themselves not new. However, from a technical perspective, Lotio differs from previous art in a few ways. First of all, the Lotio stackup is extremely simple compared to that of conventional electrochromic displays and can be constructed with DIY-friendly methods. We placed the condition early on in the design process that materials used be non-toxic and backyard-degradable. Figure 6.5 shows two of the most common electrochromic display pixel geometries alongside Lotio's geometry. Conventional electrochromic displays comprise an active electrochromic layer and an electrolyte layer sandwiched between two conductive electrodes, at least one of which is transparent. They may also be fabricated in an "open-faced" or co-planar geometry, whereby two electrodes are placed side by side, with an electrochromic layer deposited on top of one or both electrodes and an electrolyte encapsulating the whole stack. Lotio most closely resembles the co-planar geometry but additionally eliminates the extra electrode layer by using just a thin layer of electrochromic ink that is both conductive and electrochromic, as I discuss subsequently.

Using a single material that doubles as electrodes and an active electrochromic layer greatly simplifies fabrication complexity and cost, allowing Lotio to be made readily in a standard makerspace or even at home without almost no technical expertise. In addition, Lotio combines output and input in that single layer, enabling input in the form of resistive sensing: segmented portions of the design can function as buttons and other interactive elements. As I will describe, a connected microcontroller can use electric current signatures to differentiate between press-touches with no lotion present, lotion application, and press-touches with lotion present. I also use current signatures to determine which class of lotion has been applied (e.g., sunscreen, moisturizer).

Furthermore, the electrolyte in a conventional electrochromic display is manufactured into the display and is not designed to be modified by the user. In fact, the electrochromic display is often encapsulated to prevent liquid in the electrolyte from evaporating. In contrast, Lotio uses common lotions and creams as electrolytes that are applied after initial fabrication. Lotio's visual transformations require both the presence of lotion and a voltage differential: without lotion, Lotio is an open circuit that is static; without voltage, the display architecture is "complete," but there is no force driving the movement of charge required to trigger visible changes. Lotio leverages the temporality of the un-encapsulated, absorptive nature of the applied lotion, empowering the wearer as an agent who can fabricate and un-fabricate the electrochromic display at will.

6.4.2 Materials

Because Lotion Interfaces applied to the skin will likely be removed in a few hours' or few days' time, we are obligated to choose materials that can be degraded or disposed of in an environmentally responsible manner. All materials for Lotio are selected to be not only safe for application on the human body but also easily degradable in the environment without industrial recycling, biodegradation, or composting conditions.

Electrochromic Ink: The electrochromic ink base is PEDOT:PSS. The chemical structure of PEDOT:PSS is shown in Figure 6.6. Key properties of this material are electrochromism, high conductivity, mechanical flexibility, and on-skin safety. PEDOT:PSS is also non-cytotoxic [229] and becomes bio-degradable in the presence of hydrogen peroxide, which is readily accessible and environmentally friendly [44]. The PEDOT:PSS is mixed in a 7:3 ratio with dimethyl sulfoxide (DMSO), a natural solvent extracted from wood that is available as an anti-inflammatory prescription or dietary supplement. DMSO is added to enhance the mechanical stability and electrical conductivity of the resulting PEDOT:PSS layers [183].

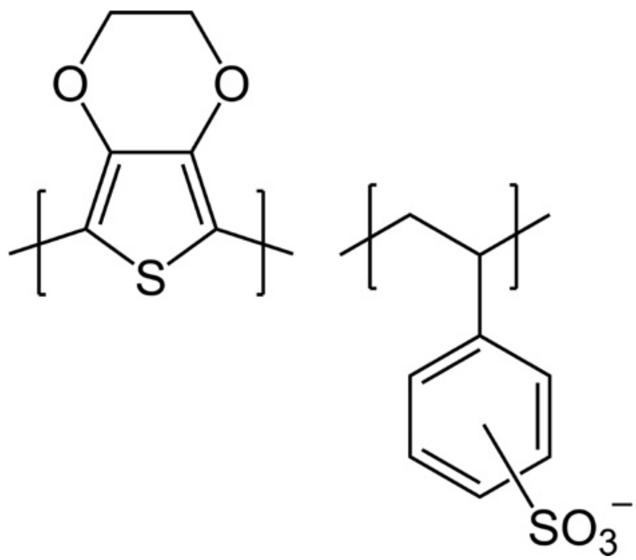


Figure 6.6: Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), an easily degradable electrochromic polymer

PEDOT:PSS is commonly used in electrochromic displays, both commercially available [390] and in research [135, 11]. These displays use PEDOT:PSS as an active electrochromic material but do not take advantage of PEDOT:PSS's conductive properties, instead sandwiching the PEDOT:PSS between two electrodes made from another material. Indium tin oxide (ITO) is perhaps the most popular electrode choice today because it is highly conductive and optically transparent, but it is very expensive, relying on the rare and rapidly depleting element of indium and requiring physical vapor deposition in a cleanroom [281]. Additionally, ITO is brittle, making it unsuitable for applications requiring conformation to irregular surfaces, such as skin.

PEDOT:PSS is one of the most cited alternatives to ITO for flexible electronics devices, demonstrating success as an electrode in organic LEDs [163], solar cells [90], and epidermal electronics [349]. PEDOT:PSS is particularly well suited to applications on the skin because it is stretchable [197]. However, such demonstrations to date use PEDOT:PSS as a conductor but ignore the electrochromism of the material. For instance, several on-skin interfaces use PEDOT:PSS as a conductive electrode but use separate materials as active electroluminescent [366, 371] or mechanical [378] layers. As previously discussed, I utilize both the electrochromism and conductivity of PEDOT:PSS. As such, separate layers are not needed for conductivity and display, reducing cost and fabrication complexity.

Substrate: PEDOT:PSS layers may be formed on many different kinds of substrates, including plastic, fabric, silicone, and paper. Different wearers may find that different substrates are more (or less) comfortable or compatible with their individual skin types. In this chapter, I present results with 2 different kinds of substrates. The first is cellulose acetate, a transparent, bio-degradable material made from cellulose, the fiber in trees and other plants. I pair the cellulose acetate with a temporary tattoo adhesive to adhere it to the skin. Cellulose acetate is flexible, conformable, transparent, and smooth, making it easy to form conductive, uniform films of PEDOT:PSS. However, it has the drawback of not being permeable, which, as noted before, is undesirable in preserving lotions' customary use. As an alternative, I also use paper surgical tape[2] as a substrate. This material is commonly used in medical applications to secure a bandage to a wound. Surgical tape conforms to the skin, allowing for seamless body integration and comfortable wear. In addition, this material is breathable and allows for lotions to absorb through it into the skin, better enabling temporal interactions with lotion. One drawback of surgical tape is its rough surface, which makes it more difficult to form uniform PEDOT:PSS films and to achieve crisp visual effects. When working with surgical tape, I mitigate this by gently sanding the surface before coating. With both substrates, to remove Lotio, the substrate is simply peeled off the skin, similar to removing a band-aid. Because my ink and substrates are all readily bio-degradable, Lotio may easily be disposed of in an environmentally responsible way without the need for special industrial processes.

Lotion: A successful electrolyte for electrochromic displays has an abundance of mobile ions to enable the reduction or oxidation reactions that occur in the active material. It is ideally in a liquid or gelled state to maximize surface area contact with the electrochromic layer. I found that many commercially-available lotions and creams are compatible with Lotio without need for modification. I evaluated sunscreen, medicinal ointment, moisturizer, and hand sanitizer; however, there are many other lotions and creams that are electrically conductive and suitable for Lotion Interfaces. As I will describe, Lotio may react differently to different kinds of lotions, which is a property that could be leveraged and considered during the design process.

6.4.3 Fabrication

Lotio is easy and affordable to produce using commercially available materials and a DIY methodology. Furthermore, Lotio is highly customizable and can be tailored to fit the wearer's personal style. First, I coat the substrate (i.e. cellulose acetate or surgical tape) with the electrochromic ink using an airbrush (Figure 6.7a). While PEDOT:PSS is considered skin-safe once dried [257, 41, 266], its Safety Data Sheet[3] recommends standard personal protective equipment, such as gloves, when handling, possibly due to the slight risk of exposure to residual solvents from the synthesis process. Airbrushing is done on a hotplate

[2] 3M™ Micropore™ Surgical Tape, 3m.com

[3] https://www.sigmaaldrich.com/US/en/sds/aldrich/655201

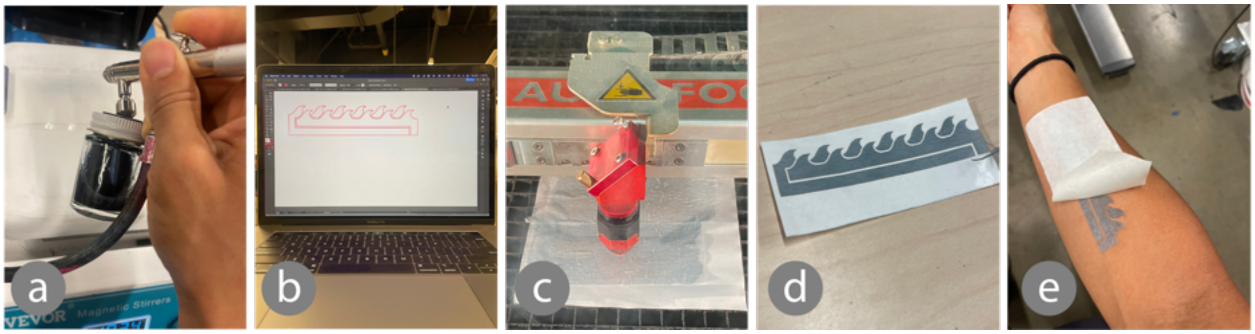


Figure 6.7: The fabrication process for Lotio. a) Coat substrate with PEDOT:PSS/DMSO ink via airbrushing. b) Design electrode shape and layout interconnects. This could be automated with a future specially designed layout tool. c) Cut the substrate using commercial laser cutter. I apply the cellulose substrate to sticky tattoo paper and the surgical tape substrate to waxy paper before cutting. d) Remove excess substrate so that only the design remains. e) Transfer resulting design using transfer tape to the skin.

set at 120°C, which helps the ink dry uniformly onto the substrate and also increases the conductivity of the PEDOT:PSS [87]. I leverage airbrushing on a hotplate because it allows thin, even layers to be formed on a variety of substrates without complex ink formulation or parameter tuning processes. I also experimented with screen-printing but found that it was difficult to form uniform ink layers; on cellulose acetate, PEDOT:PSS beaded up and rolled off the substrate, and on surgical tape, the PEDOT:PSS soaked into the substrate where it was initially applied and did not spread well. Inkjet printing [157] is a potential alternative to airbrushing, although it demands more calibration, and existing reports of printing with PEDOT:PSS [266] rely on proprietary PEDOT:PSS formulations with undisclosed solvents.

After airbrushing, I use a laser cutter to cut the substrate to the desired shape (See Figure 6.7b&c). This allows for detailed designs with a high level of precision. I draw the designs manually in Adobe Illustrator, but a specifically designed layout tool could assist in the automatic creation of masks for more complex designs, potentially with multiple layers and multiple different PEDOT:PSS thicknesses within the same module. Finally, I use transfer tape to apply the design to the skin (See Figure 6.7e). After drying, the layer of electrochromic ink is only on the order of 1µm thick, so Lotio is effectively simply as thick as the substrate — 100µm for cellulose acetate and 50µm for surgical tape. This allows it to be lightweight, conformable, and comfortable on the skin.

Once fabricated, Lotio can simply be wired to input or output pins on a microcontroller using copper tape as a connector. Except where otherwise mentioned, I use an Arduino Uno to power and control Lotio in this chapter, but more compact options are commercially available. For example, Lotio can be powered directly by connection to a battery or controlled by a small ATtiny85 microcontroller that is in turn powered by a CR2032 3V coin cell battery, as seen in Figure 6.8. Looking to the future, as illustrated in Figure 6.4, I envision Lotio to be integrated with lightweight wearable devices, such as an electronic ring (Figure 6.4, left), electronic garment (left-center), or smartwatch (right-center). All Lotio prototypes shown in Figure 6.4, as well as all figures in this chapter, are functional. However, the prototypes in Figure 6.4 are not electronically connected to the wearables that they are pictured with; instead, the Lotio prototypes are connected to a hidden 3V coin cell battery, actuated with lotion, and then placed alongside wearables to illustrate how integrated future systems might look.

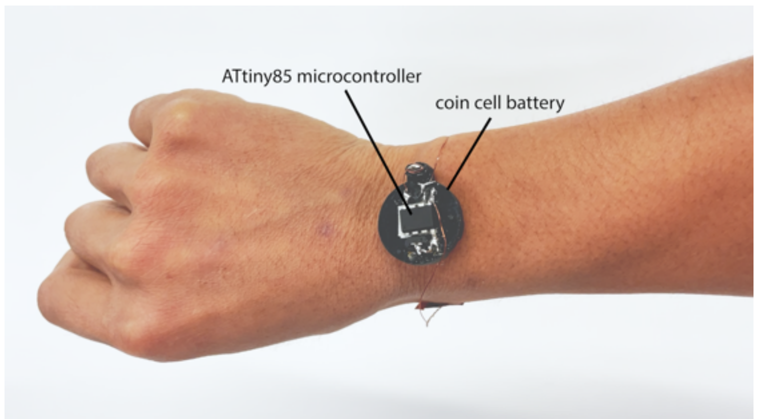


Figure 6.8: Lotio may be powered and controlled by a ATtiny85 microcontroller and a 3V coin cell battery.

6.4.4 Design Parameters

Lotio is highly customizable and aesthetic. I expand prior works that utilize conductive traces as an aesthetic element of the design by integrating display capabilities [203, 146]. In addition to spatial layout, a designer may modulate different parameters that affect interactions with Lotio. Namely, layer thickness affects not only the initial visual appearance of the design but also the rate at which a design element changes color (switching rate). It also affects resistance and thus power consumption. Applied voltage similarly affects switching rate and power consumption. These may further couple with the effects of different lotion types, providing designers with several variables to tune their desired interactions with Lotio. I detail the effect of these parameters in the next section.

6.5 Characterization

6.5.1 Effect of Layer Thickness

The thickness of the PEDOT:PSS layer is an important variable in determining the visual clarity of Lotio. Visual clarity refers to the perceivable difference between positive and negative electrodes once lotion and voltage have been applied. As a metric for visual clarity, I use the Web Content Accessibility Guidelines (WCAG) 2 definition of "contrast ratio," which weighs differences in red, green, and blue color channels in an image to approximate the human eye's perceived difference in luminance between two colors[4]. For reference, white on white has a contrast ratio of 1, and black on white has a contrast ratio of 21; pure red, pure green, and pure blue on a white background have contrast ratios of 4, 1.4, an 8.6, respectively. Visual clarity depends on the density of PEDOT:PSS in the electrochromic ink. To influence visual clarity, designers can modify the thickness of electrochromic ink by diluting the concentration of PEDOT:PSS in the ink, by decreasing the pressure of the airbrush, or by decreasing the time the airbrush is swept across the substrate.

Figure 6.9 shows the effect of layer thickness on visual clarity. The prototypes in the figure are 5.08cm x 2.54cm. For all layer thicknesses, the designs are quasi-bistable, meaning that the color change is retained for some amount of time (over 10 minutes) after the removal of voltage. As can be seen in Figure 6.9, the maximum contrast ratio under an applied voltage of 5V is achieved at a layer thickness of 1230nm (1.23µm), corresponding to a PEDOT:PSS mass loading of 0.12mg/cm^2. Layers thinner than this suffer from poor conductivity, and layers thicker than this become quite dark at baseline, making it more difficult to perceive the darkening effect on the negative electrode. I use this thickness for the remainder of the characterization results presented here.

6.5.2 Effect of Applied Voltage

Figure 6.10 shows images of a Lotio prototype applied to the skin under voltages of 1 to 5V. The contrast ratio increases for increasing voltages. The applied voltage may be arbitrarily inverted and reverted between the two electrodes to achieve a dynamic, alternating color effect.

Applied voltage also has a strong effect on the time it takes for Lotio to saturate in color ("switching time") as well as the current consumed during switching (see Figure 6.11). I measure switching time as the elapsed time between the initial application of a voltage and the time at which electrodes reach their saturated color (i.e. the maximum contrast ratio between the two electrodes). This was first measured by hand in real-time and then refined by reviewing a video recording of the transformation. As applied voltage increases, switching time decreases and switching current increases. Still, for electrodes with area 6.5cm^2, the peak power consumption with an applied voltage of 5V is only 350µW.

6.5.3 Differentiating Touch

Lotio is capable of sensing and differentiating between touches before lotion is present and during the application of lotion. Figure 6.12 plots current through a Lotio overlay during different events. When Lotio is powered to 5V, there initially is no current flowing through

[4] https://webaim.org/articles/contrast/

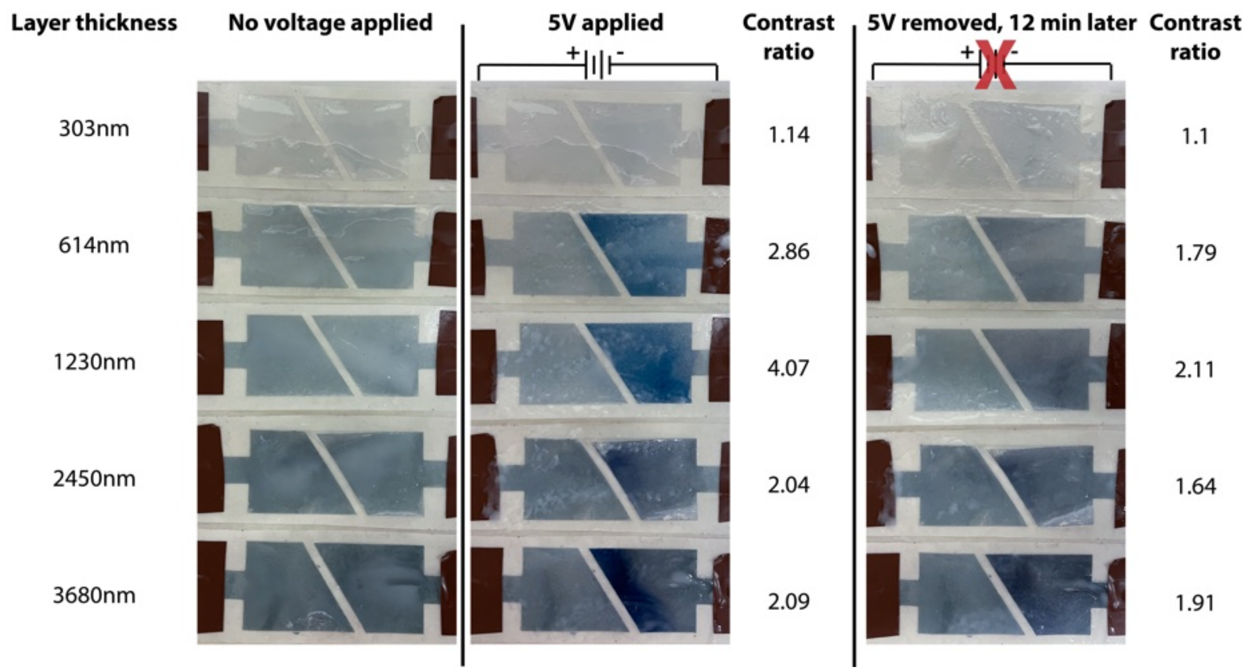


Figure 6.9: Visual clarity of Lotio prototypes with varying thicknesses of PEDOT:PSS. Prototypes are 5.08cm x 2.54cm. Left: baseline Lotio prototypes with lotion applied but no voltage; Middle: Lotio prototypes after lotion has been applied with a 5V voltage (negative electrode is on the right). Right: Lotio prototypes 12 minutes after the 5V voltage has been removed, demonstrating Lotio's quasi-bistability.

the design. Before lotion is present, touching Lotio with a finger essentially closes the electrical circuit through skin resistance, and a spike of 30µA is observed (Figure 6.12, green). There appears to be no detectable difference between touching or pressing with different forces. When lotion is applied, current increases to and stabilizes at a higher value than can be achieved with a simple finger touch (Figure 6.12, gray). Subsequent touches once lotion is applied and still "wet" on the skin decrease the circuit resistance even further and lead to spikes in current on top of the lotion baseline (Figure 6.12, red). A controller for Lotio can easily be programmed to detect these current signatures. While my implementation leverages resistive sensing, future work could utilize Swept Frequency Capacitive Sensing [291] to eliminate potential confounds between lotion type and lotion amount.

6.5.4 Effect of Different Lotions

I tested the effect of 4 different types of lotions, gels, and creams: a mineral sunscreen, a prescription (Rx) steroidal skin ointment for psoriasis, a moisturizer gel, and an alcohol-based hand sanitizer. Figure 6.13 shows the sample swatches under an applied voltage of 5V. For this test, I used a surgical tape substrate, because the hand sanitizer wiped the

Figure 6.10: Visual clarity of Lotio under an applied voltage of 1 to 5V. In the top row, the positive voltage is connected to the top part of the design with the bottom part of the design grounded. In the bottom row, the voltage is reversed.

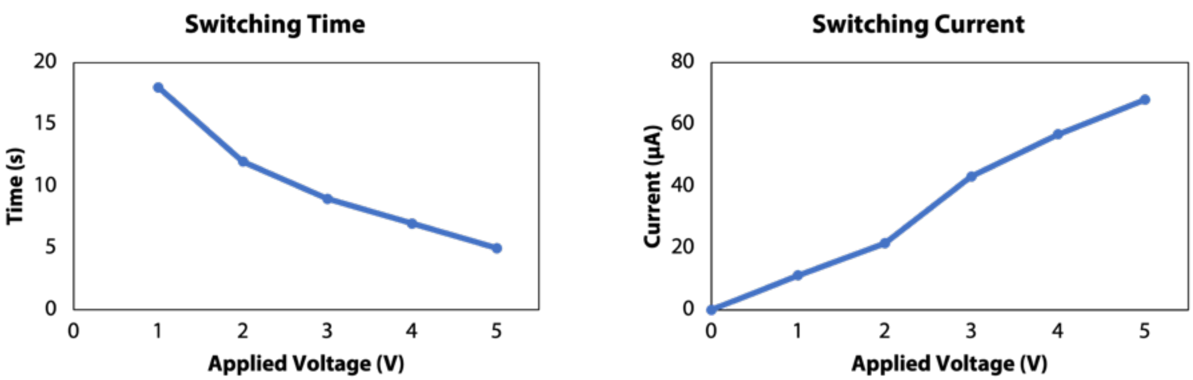


Figure 6.11: Left: Switching time (measured from time of initial voltage application to time when color saturates) vs. applied voltage. Right: Switching current vs. applied voltage.

PEDOT:PSS layer off the cellulose acetate substrate entirely. The 4 different lotions all induced visible color changes but varied in visual contrast at saturation and switching rate, corresponding to different current signatures.

As seen in Figure 6.13, the sunscreen and moisturizer induced the fastest switching (under 3 seconds) and greatest visual changes. The prescription ointment induced a much

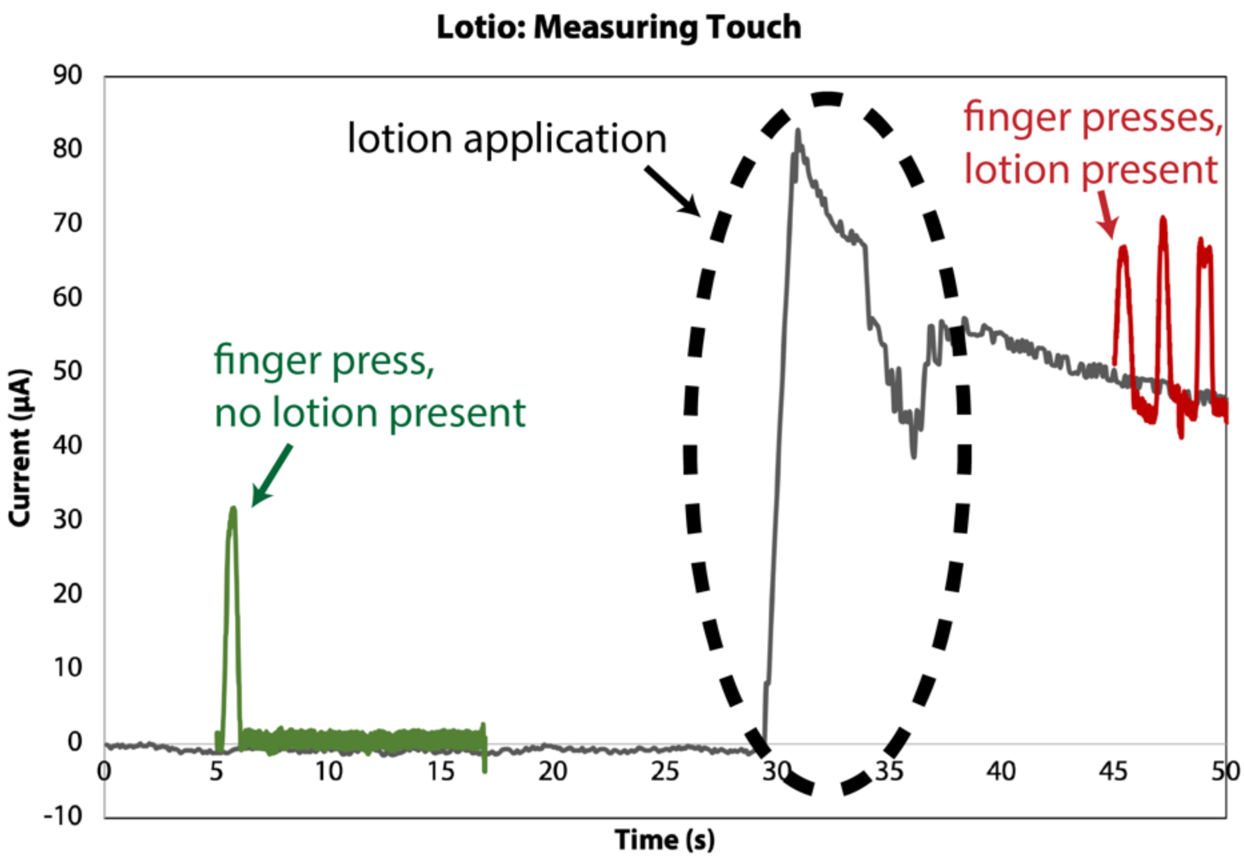


Figure 6.12: The application of lotion over Lotio, a press-touch with no lotion present, and a press-touch with lotion present all have different current signatures. This may be leveraged to provide different interaction modalities mediated by the application of lotion.

slower (∼15 seconds) and more subtle, but still noticeable, change. Even alcohol-based hand sanitizer was able to serve as an electrolyte to some degree, inducing switching within 3 seconds. However, the hand sanitizer also partially damaged the electrochromic ink as it was rubbed on, which is why only small areas of the negative electrode are visibly darker in Figure 6.13. In addition, the reversion time once the applied voltage was removed was only ∼1 minute (compared to >10 minutes for the other lotion types tested), likely due to the rapid evaporation of alcohol from the substrate. Different lotions may also be used on the same Lotio interface. Once one lotion is absorbed, evaporated, or simply wiped off, the application of another lotion (of the same or different type) reactivates Lotio as expected.

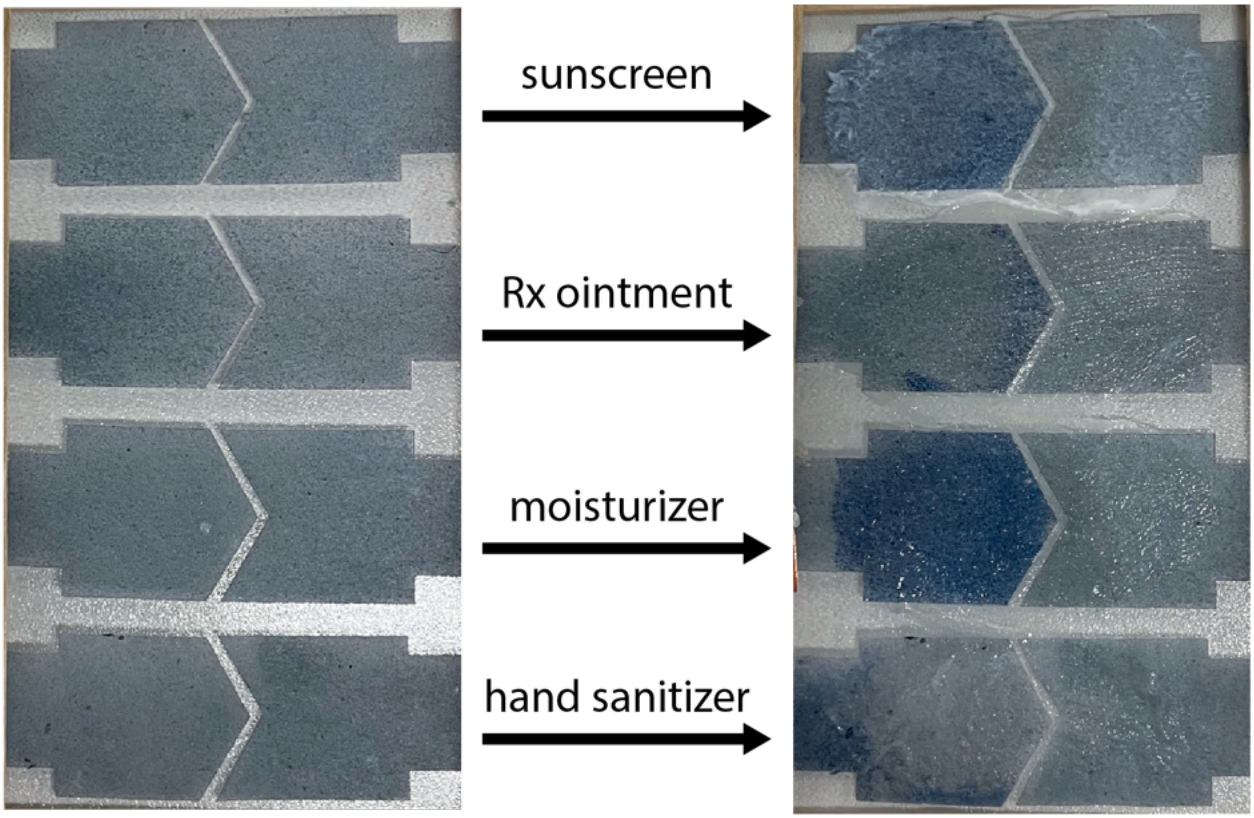


Figure 6.13: Images of Lotio under different lotions, gels, and creams: sunscreen, medicated ointment, moisturizing gel, and hand sanitizer. Applied voltage = 5V, with the positive electrode on the right.

6.6 User Study

I conducted a preliminary user study with 9 participants to understand perceptions of lotion-mediated interaction and how Lotion Interfaces might differ and also share characteristics with existing on-skin technologies. This user study was reviewed and approved by UC Berkeley's Institutional Review Board (IRB).

6.6.1 Participants And Procedure

Participants ranged in age from 19 to 41 years old (avg. 24.9 years). 5 participants identified as women, 3 participants identified as men, and 1 chose not to specify. Participants were recruited from local university mailing lists and invited to meet in our lab for an hour. They were compensated at the rate of $20/hour.

First, I applied lotion to Lotio on a white backing and asked participants to describe any visual changes they noticed. After becoming familiar with the visual characteristics of the display, participants were invited to wear the prototype on a body location of their choosing. All participants opted to try out the prototype. During the user study, the prototype was actuated at 5V. Finally, I conducted a semi-structured interview to garner thoughts and reactions to the presented prototype and interaction. All interview meetings were audio recorded, transcribed, and analyzed, following best practices for a qualitative interview [369].

6.6.2 Findings

> The way it changed the shade and the saturation, the density of the ink, right before my eyes and on my skin felt really interesting (P1).

> The way it changed the shade and the saturation, the density of the ink, right before my eyes and on my skin felt really interesting (P1).

Participants wore Lotio on their hands, wrists, and forearms. All participants found these locations to be ideal for skin-worn technology, echoing prior work [113]. In addition, 4 participants envisioned wearing Lotio on the face or neck. In deciding appropriate locations for Lotion Interfaces, participants were concerned with visibility, accessibility, and existing cosmetic practices. Some participants considered Lotio's audience, determining where to wear the interface to facilitate different types of interactions.

> I would wear Lotio] somewhere where not everyone can see it, so it's more of a private informative piece that I can reveal important information about my body to myself (P6).

> I would wear Lotio] somewhere where not everyone can see it, so it's more of a private informative piece that I can reveal important information about my body to myself (P6).

> It could be a signal to other people too, if I wore it on some other place where I couldn't see it but other people could (P5).

> It could be a signal to other people too, if I wore it on some other place where I couldn't see it but other people could (P5).

Seven participants envisioned using Lotio for health monitoring and medical applications: measuring sweat (P5), body temperature (P3, P5), and UV exposure (P2). Participants also imagined using Lotio to display health data sensed on other devices: blood sugar levels (P3, P9), heart rate (P3, P5, P9), and hydration level (P6). P6 thought that a Lotion Interface would be particularly well suited to "surfacing relevant body data" because "the act of applying lotion itself could be seen as a self-care activity." Participants also envisioned using Lotio for aesthetics, notifications, and as an input other devices. Two participants wanted to use Lotio as a form of nonverbal communication, "reflecting emotions" and behaving as a "subtle social cue." Participants liked that the interface attached directly to the skin and likened it to an extension of self.

> It's fundamentally different because it feels like it's sort of becoming one with your body instead of just an external device that is registering things about your body (P2).

> It's fundamentally different because it feels like it's sort of becoming one with your body instead of just an external device that is registering things about your body (P2).

> It's like just adding on to your skin (P3).

> It's like just adding on to your skin (P3).

The prototypes used in the user study were not micro-perforated, hindering the absorption of lotion in the area of the skin to which the prototypes were applied. Participants responded negatively towards this aspect, finding it unnatural and in opposition to prior experiences with lotion. This highlights the need for Lotion Interfaces to *allow absorption*. In addition to micro-perforating a cellulose substrate, a more permeable substrate may instead be used (e.g., surgical tape as seen in Figure 6.13). Fibrous substrates come with the drawback of being rough and thus difficult to make conductive; however, they allow for the absorption of lotion through the design.

Five participants desired further body integration, envisioning a more "permanent" embodiment.

> I would actually like if it's a permanent tattoo and it was just there 'cause that lowers the fact that I have to put it on everyday (P5).

> I would actually like if it's a permanent tattoo and it was just there 'cause that lowers the fact that I have to put it on everyday (P5).

Several participants found the concept of lotion-mediated interaction "seamless" and imagined incorporating Lotio into their daily cosmetic routines: "styling" it each morning as one would their hair or makeup. While this preliminary user study provided initial insights into lotion-mediated interaction, further evaluations are necessary to assess and contextualize this new interaction paradigm.

6.7 Envisioned Applications

I present here a selection of envisioned applications for Lotion Interfaces. These interactions are inspired by conversations with user study participants, as well as my experience designing Lotio and other on-body technologies. I describe the applications in terms of Lotio's capabilities; however, they may be extended to other types of Lotion Interfaces more generally (e.g., the enacted transformation may take other, non-visual forms).

6.7.1 Personal Health Care

The semantic priming enabled through Lotion Interfaces makes them especially effective for displaying personal health data and providing positive feedback for building healthy skin-related routines. Sensing applied moisturizer, a Lotion Interface may pull hydration metrics from the user's smartphone and display them on the skin, simultaneously providing useful information and adding a pleasing aesthetic experience to the act of applying the moisturizer. Similarly, sensing applied Valerian oil[5], the same Lotion Interface may instead pull biosignals related to stress and dynamically update the on-skin design to promote more calmness and reward the user for taking the step to apply Valerian oil. Lotion Interfaces can also be used to track habits associated with the skin: for instance, monitoring the frequency of sunscreen application. The Lotion Interface can display frequency information at the time of application. The fact that Lotion Interfaces only activate when a lotion or cream is applied can be advantageous in situations when live updates in health data may be distressing. For example, in times of unavoidable stress, we might not want an on-skin display to constantly update, which might only heighten anxiety; instead, we might want updates only when we take the time to practice self-care via the application of Valerian oil or other calming topical substances.

6.7.2 Dynamic and Temporal User Interfaces

Similar to existing on-skin technologies [146, 205, 361, 364, 371], Lotion Interfaces can be used to provide input to external devices. Wearers can use the interface to play/pause music that they're listening to, answer phone calls, or control an external display. Lotion Interfaces may sense touch input both with and without lotion present and can differentiate between the two states. This adds an additional modality to on-skin interactions. For instance, touch interactions on a dry Lotion Interface connected to a music player might simply toggle between songs, but when therapeutic or restorative lotion is applied, the music player could transition to a soothing and relaxing playlist, seamlessly enhancing the experience of the self-care routine of applying lotion. Furthermore, lotion can add a temporality to skin-based interactions. When taking a break to apply lotion, a wearer may wish to activate a user interface that would normally be too distracting to have always available. Once the interaction is complete and the lotion is absorbed or removed, the Lotion Interface reverts back to a static display, disconnecting the wearer from potentially distracting updates.

The temporal nature of Lotion Interfaces may also be coupled with health applications. For example, a visual interface such as Lotio could change color when hand sanitizer is applied, or a future tactile Lotion Interface may change texture to mimic a reassuring squeeze; this initially provides positive feedback for the act, and furthermore, as the design fades, the wearer is subtly reminded to re-apply sanitizer soon. Similarly, Lotio could help keep track of applications of topical steroidal medications that should not be applied too often; a lingering

[5] Valerian oil is commonly used as an herbal remedy to promote sleep and calm anxiety [117].

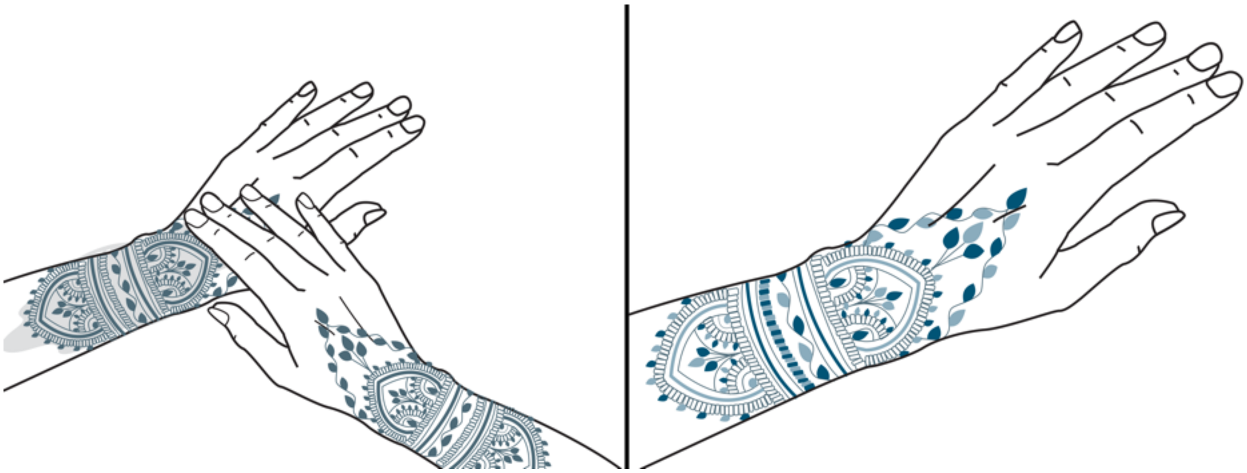


Figure 6.14: Henna-inspired embodied data stream. The weekend following her wedding ceremony, Payal admires the henna-based Lotion Interface still visible on her forearms and hands. Applying essential oils, Payal notices her Lotion Interface begin to ebb, with portions becoming darker in appearance and other portions becoming lighter. She knows that her Lotion Interface is tied to the use of her wedding hashtag online, but has no way to concretely interpret the visualization. She appreciates the dynamic nature of the interface, and feels delight in thinking about her family and friends that were able to attend the celebration.

dark blue design might help remind the wearer that they need to wait before reapplying their medication.

6.7.3 Dynamic Personal Expression

Lotion Interfaces lend themselves well to dynamic personal expression. A Lotion Interface could be worn on the face as a form of dynamic makeup. Applying lotion to this interface may cause the makeup to transition from day to night, with material around the eyes darkening for a more dramatic look (See Figure 6.4, right for an example of a cosmetic Lotion Interface). I also envision Lotion Interfaces being used in playful, performative, and abstract manners. For instance, Lotion Interfaces could embody a connected data stream. When the wearer applies lotion, the interface pulls data from the stream and updates accordingly. The concrete values of the data may be unknown to the wearer, who simply experiences the abstract and aesthetic nature of their changing Lotion Interface (See Figure 6.14). In this scenario, data inhabits physical space on the surface of the wearer's body as a form of "vibrant matter" [24]. Participants in the user study were particularly drawn to Lotio *as* it was changing. Inspired by participants' fascination, Lotion Interfaces could be used as an animated skin display. After the lotion is applied, but before it is absorbed, the display elements could ebb and flow, fluctuating randomly or in a pattern.

Lotio may also be patterned such that a design or message is revealed only when lotion is applied (see Figure 6.15, which is a 13.5cm x 10cm prototype actuated by 3V). In this way, Lotio can provide new opportunities for playful experiences with friends.

Sally receives a Lotio patch from Lilly in the mail. The design looks like a decorative abstract circular tattoo. The next morning when getting ready for work, she excitedly puts it on her arm. Later that day, Sally is feeling stressed and reaches for her lotion infused with soothing lavender oil. Nervously rubbing it all over her hands and arms, she notices that her Lotio patch from Lilly has transformed into a pulsating heart. Smiling, she thinks of Lilly and is overcome by a sense of happiness and gratefulness for their friendship. Feeling refreshed and re-centered, she returns to work.

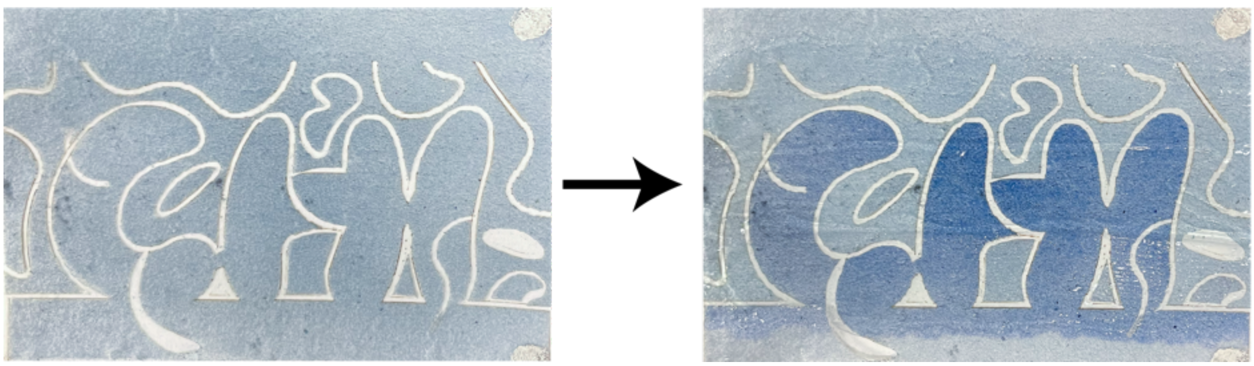


Figure 6.15: Lotio may be patterned to reveal a message that becomes obvious only once lotion is applied. The prototype shown is 10cm tall and 13.5cm wide and actuated with 3V. The letters "CHI" appear after the application of lotion.

6.7.4 Integration with *Vims*

As mentioned in Chapter 5, Lotio is low power enough to be powered by a *Vims* bracelet over multiple lotion activations in a given day. The schematic of this 100% backyard-degradable wearable is shown in Figure 6.16.

A charged *Vim* bracelet, as described in Chapter 5 can be tied or adhered onto the wrist such that Lotio's electrodes contact those of the *Vim* bracelet. Initially, the system is in an open circuit configuration, with no power consumption. When lotion or another activating conductive gel or cream is applied, it acts as an electrolyte, closing the circuit and allowing free ions to migrate towards the electrodes. An example envisioned interaction is shown in Figure 6.17. An individual may apply a customized patch as they would a temporary tattoo and connect it to a *Vim* bracelet. When lotion or activating gel is applied onto the skin, it completes the electrochromic circuit, and selective areas of the design turn deep blue. This could be used to simply make a fashion statement, to reveal a hidden message from a friend who gifted the wearer the design, or to serve as an aesthetic, positive feedback mechanism or reminder for lotion-related self care, among other applications. At the end of the day or week, when the wearer is tired of the design, the whole system may simply be

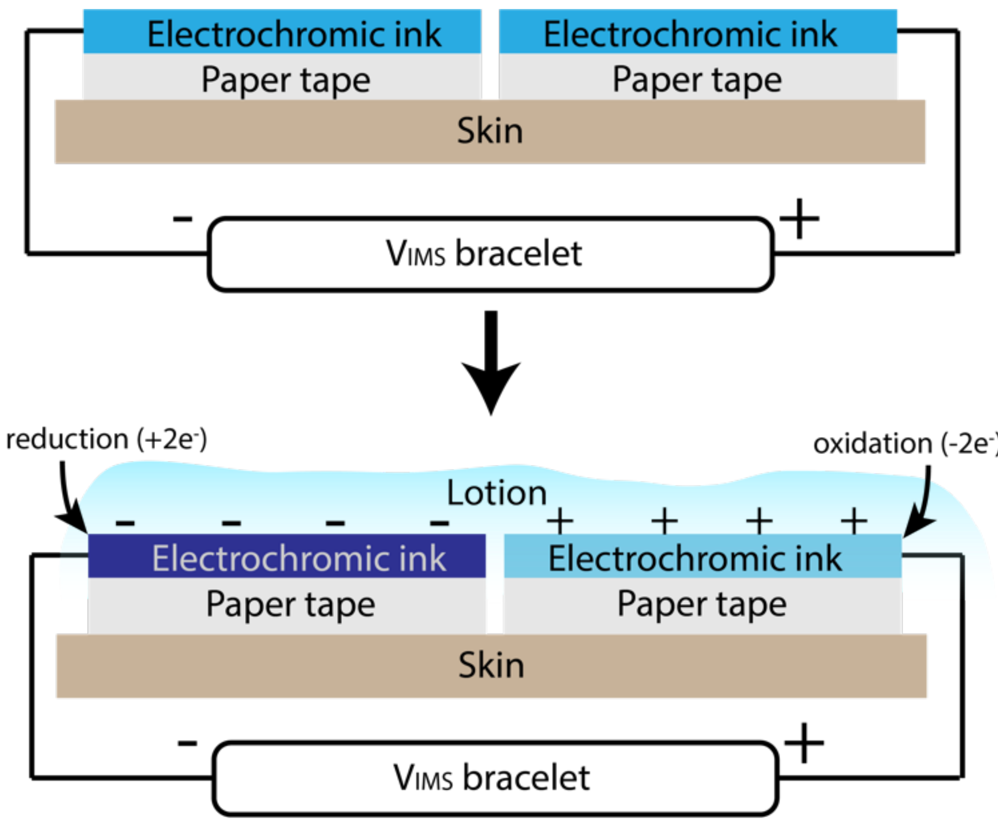


Figure 6.16: Schematic of the *Vims*-powered Lotio, a 100% backyard-degradable wearable.

peeled off from the skin like a band-aid. It can be soaked in hydrogen peroxide for a day to effectively degrade the PEDOT:PSS ink [44] and then tossed into the backyard, where it quickly decomposes and enriches the soil.

6.8 Discussion

6.8.1 Mediated Ambient Displays

Data displayed on the skin can be abstract or representational, emissive [366] or non-emissive [205], eye-catching or more subtle. While Lotion Interfaces can be any of the above, they are particularly well suited for a new kind of semi-ambient displays. The wearer does not need to dedicate subconscious attention to monitoring their skin-worn display for changes, because they know it will only update when lotion is applied. At this point, the user is already subconsciously thinking about their skin, and is primed to notice changes in its appearance. Ambient Lotion Interfaces such as Lotio contribute to the growing body of work examining the potential for ambient displays on the body [65, 69, 118]. Because Lotion

Figure 6.17: A 100% backyard-degradable wearable. *Vims* are chained in series as a bracelet and contact the electrodes of a simple *Lotio* design. When lotion is applied as an electrolyte, parts of the design change color, revealing a hidden message (in this case, "CHI").

Interfaces are mediated by lotion application, however, they provide novel opportunities for designing for situations in which the wearer has a say in when their wearable displays are activated. As previously discussed, wearers may not always wish to be vulnerable to data updates, especially in times when they do not feel in control of the data being displayed, such as during a stressful situation. They may wish to only invite subtle changes in their Lotion Interface when they actively apply or have recently applied something to their skin, indicating that they are in a more relaxed or otherwise self-caring mood. Additionally, unlike existing on-skin interfaces, because lotion is necessary to close a Lotion Interface's electrical circuit, no power is consumed when the Lotion Interface is dry, so Lotion Interfaces may be sustained for extremely long periods of time with virtually no effect to the battery life of a device that may power it.

6.8.2 Expanded Embodiments

As mentioned, Lotio is just one of potentially many Lotion Interfaces. While Lotio's form factor is an overlay on the surface of the skin, there are many other ways that Lotion Interfaces can be integrated with the body. Lotion-reactive materials could be integrated into make-ups [143], henna, nail art [161], and more permanent body decorations like tattoos [343]. Rather than changing visual appearance, Lotion Interfaces could alter the texture of skin [362, 149] and other properties. Expanding the notion of lotion to include hair gels, mousses, and creams, I can consider novel interactions with dynamic hair [71, 341].

Lotio is admittedly a rather simple visual embodiment of Lotion Interfaces, but similar principles could be extended to make more complex displays. For instance, I could leverage the dependence of contrast ratio on applied voltage (Figure 6.10) to display more bits of information. Additionally, instead of using the same thickness of PEDOT:PSS for both the cathode and anode, which results in two always-visible elements, I could make the cathode very thin such that it is virtually invisible, allowing for the control of the anode as a single conventional display pixel. This could be achieved by modifying my fabrication procedure

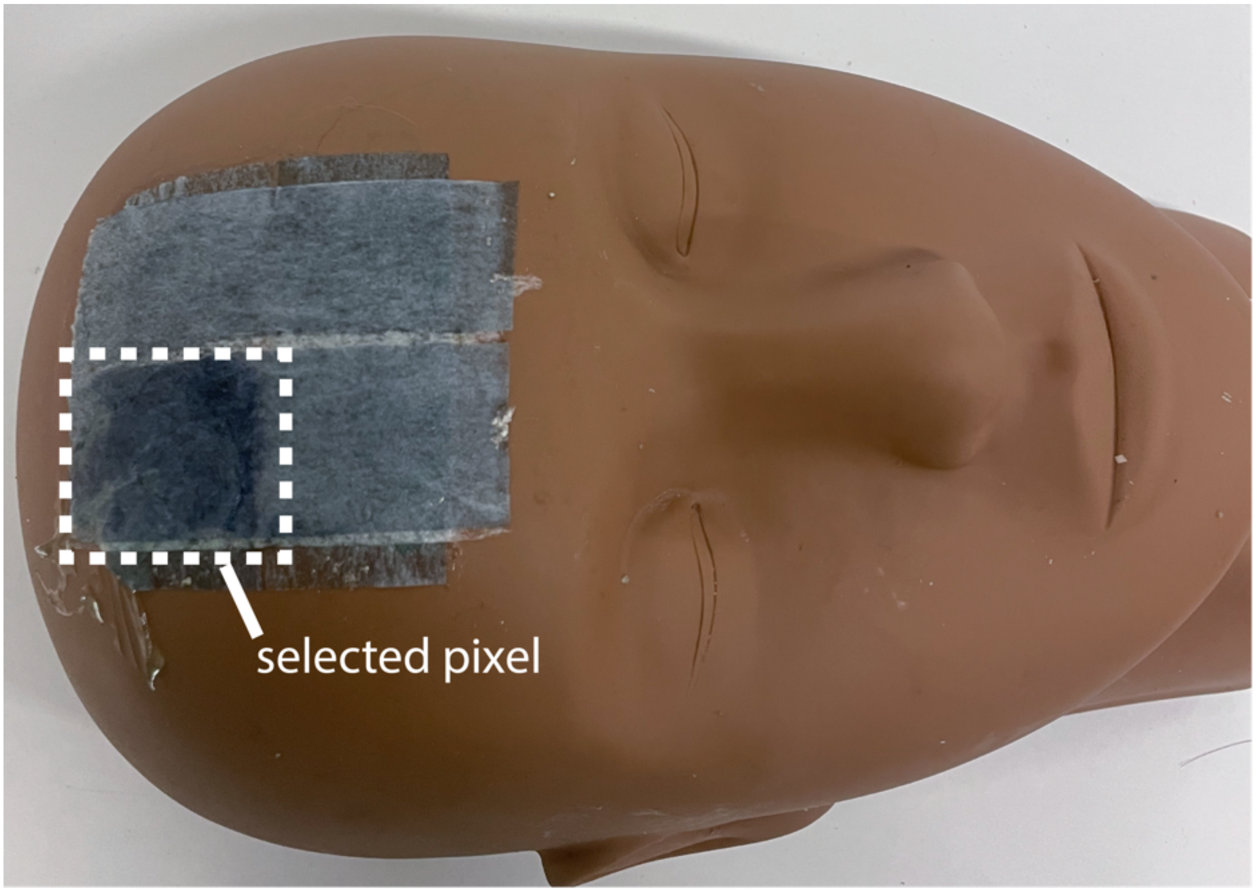


Figure 6.18: A multi-layer 2x2 pixel Lotio prototype. The pixel in the dashed box has been selected and actuated by applying voltage between its respective row and column.

slightly – instead of airbrushing the electrochromic ink onto the substrate and then cutting the substrate, different vinyl stencils may be cut, and those may be used as masks to airbrush design elements with different thicknesses onto the same substrate; such a technique could also be used to create different levels of contrast within the same design (Figure 6.9). Finally, with slightly more fabrication steps, Lotio may be adapted from its present co-planar geometry to be a multi-layer "sandwich" structure, which would allow for the creation of generic 2D displays that can display arbitrary information on the fly. Figure 6.18 shows a preliminary 2x2 pixel prototype of this that uses 2 layers of PEDOT:PSS-coated surgical tape separated by a single layer of insulating surgical tape. When lotion is applied, it is absorbed through the surgical tape layers, and selective pixels may be activated by addressing (i.e. applying a voltage differential across) particular rows and columns, similar to a conventional passive matrix display.

Beyond Lotion Interfaces that are based on visual changes, embodiments that utilize other materials that create textural, haptic, or even olfactory changes could expand the richness of our interactions with lotions. Lotion might rehydrate integrated hydrogel beads, such as those used in Jain et al.'s underwater morphing artifacts [134], to create shape changes that are both visible to others and perceivable by the wearer. Lotion might also chemically react to a Lotion Interface to produce heat.

6.8.3 Beyond the Body

Thus far, I have highlighted the novel aesthetic, playful, and useful interactions that Lotion Interfaces on the skin and body can enable. However, the design space of Lotion Interfaces includes dimensions extending away from the skin as well. There are many experiences involving lotions and creams beyond personal health care and on-skin applications that could be augmented by Lotion Interfaces. For example, fabric or leather conditioners may be used to clean furniture for invited guests; Lotion Interfaces could be integrated into a sofa to customize the pattern of the sofa to please the guests. Alternatively, Lotio-inspired electrochromic designs may be integrated into windows, and by rubbing a glass polishing cream onto the window may simultaneously clean the window and provide a few hours of shade or privacy. Creams and gels are also common in food, a domain that has attracted great attention in HCI in recent years [75, 62]. The implementation of Lotio described in this chapter is not edible, but it is possible that as research in edible electronics [298] uncovers applications that use a gelatinous electrolyte, edible Lotion Interfaces could transform the act of food preparation into a novel interactive experience as well. These concepts represent just slivers of the broader landscape of Lotion Interfaces that have yet to be explored.

6.8.4 Limitations

Naturally, Lotio and Lotion Interfaces more generally have limitations and face challenges that call for careful consideration when designing applications. Lotio remains operational for over 3 months and is stable over at least 20 lotion applications. However, envisioning mostly short-term applications, I have designed it to be easily degradable in the environment, which inherently limits its durability. As previously described, the electrochromic PEDOT:PSS layer is damaged by hand sanitizer, and it may also be damaged by vigorous scrubbing. Thus, more work is needed to adapt it to longer-term wear or perhaps even integration with smart garments, which may be subject to multiple washings. Additional solvents and steps to "set" the PEDOT:PSS ink, as explored in recent research in materials science [285], could be used to extend the longevity of Lotio, though this may come at the expense of making Lotio less eco-friendly.

In addition, Lotio relies on external electronics for power and control. Fortunately, the most basic implementation only requires a small battery; due to Lotio's extremely low current consumption, virtually any commercially-available battery with a voltage of 1.5V or more is sufficient. For a 3V CR2032 coin cell battery with a capacity of 240mAh, assuming 10 lotion applications a day, Lotio can theoretically be powered for 20 years, which exceeds both the expected lifetime of Lotio itself and the storage lifetime of a CR2032 battery. Even with the addition of a microcontroller for more advanced functionality, as seen in Figure 6.8, the footprint of the required electronics is still quite reasonable in size compared to existing wearables. Still, relying on external electronics does add complexity and constraints. Connecting Lotio to the electronics is a challenge that would particularly benefit from more attention in future work. I use copper tape and wires for the demonstrations in this chapter, but these are not ideal from both an aesthetic and durability standpoint. Gold traces or contacts that can be airbrushed through a stencil or inkjet-printed might be a more elegant solution, especially if they can be directly soldered to for a cleaner and more robust electrical connection. Additionally, as with any smart wearable, batteries, integrated circuits, and other electronic components susceptible to moisture must be carefully encapsulated and isolated.

Scalability is another limitation of Lotio. Lotio may readily be made in a variety of sizes, covering mm-scale areas (Fig. 6.3, left) to patches that cover half a forearm (Fig. 6.15). However, Lotio in its current implementation is not indefinitely scalable. The main reason for this is that PEDOT:PSS, while conductive, is still more resistive than ITO and other conventional electrode materials. While Ido not characterize Lotio's size limits here and while this resistance has a neglible effect on the scale of the various Lotio prototypes I present in this chapter, it may become significant for body-sized Lotio prototypes, demanding higher voltages for operation.

Finally, the development of Lotion Interfaces more generally requires future work to characterize and overcome challenges surrounding potentially confounding variables, such as moisture and sweat, that inherently exist for all kinds of Lotion Interfaces. In this chapter, I present preliminary results suggesting that Lotio, one example Lotion Interface, can react differently to different kinds of lotion, and by extension, potentially sweat or other ionic substances that might "accidentally" activate Lotio. Swept Frequency Capacitive Sensing [291] is one potential technique that might help a Lotion Interface distinguish among different types and amounts of media. In addition, because variables such as skin conductance, sweat rate, and sweat concentration vary among individuals and environments, it would be fruitful to conduct future studies characterizing the effect of these on specific Lotion Interfaces so that I may come up with systems to detect and calibrate for them.

6.9 Conclusion

In this chapter, I presented Lotion Interfaces, a novel interaction paradigm for skin-based electronics using backyard-degradable materials and accessible workflows. I outlined design considerations and opportunities for lotion-mediated interaction. As an exemplar, I presented Lotio, a dynamic skin-worn display capable of sensing and reacting to applied lotion, and discussed findings from an exploratory study with 9 participants. Lotio is not simply a backyard-degradable stand-in for traditional displays but is also a novel system that ideally encourages future designers to consider the affordances of lotion in interaction design. Furthermore, this approach can be influential beyond the skin, inspiring future designers to examine existing practices to find new embodied interaction modalities. I have focused on how lotion-mediated interactions may enrich current practices around lotion usage, but as the body of work in Lotion Interfaces becomes more rich with time, it is possible that lotions and creams may actually start to be used primarily to activate interactions with Lotion Interfaces, with their conventional uses (moisturization, cooling, fragrance, itch relief, etc.) becoming secondary. Lotion Interfaces are an example not only of how we can create individual backyard-degradable electronic components but also of how working within the constraints of backyard-degradable materials can inspire novel technologies for interactions.

Chapter 7

Unmaking

Previously, Chapters 3-6 of this thesis have focused on the strategies for *making* backyard-degradable interactive systems and the novel design opportunities that arise as a result. In this chapter, I discuss another design consideration and opportunity that designing with backyard-degradable materials supports – *unmaking* [1]. The access and growing ubiquity of digital fabrication has ushered in a celebration of creativity and making. However, the focus is often on the resulting static artifact or the creative process and tools to design it. Because backyard-degradable materials decay and are readily "unmake-able" by nature, unmaking becomes intrinsically entangled with making when designing with such materials. Nonetheless, unmaking on its own – even with non-backyard-degradable materials, is an important emerging design positionality that opens the door to unconventional political, ethical, and technical considerations for making. This chapter focuses on positioning and defining unmaking in the context of the making of tangible systems generally, beyond ones made with backyard-degradable materials. Regardless of the materials used, there is implicitly a post-making process that extends past what is, from a progressional, goal-oriented making stance, the "final," static artifact. By drawing from artistic movements such as Auto-Destructive Art, intentionally inverting well-established engineering principles of structurally sound designs, and safely misusing unstable materials, I demonstrate unmaking as an important extension to making, even when the materials used are not easily degradable (whether intentional or not). In this chapter, I provide designers with a new vocabulary of unmaking operations within standard 3D modeling tools. I demonstrate how such designs can be realized using a novel multi-material 3D printing process. Finally, I detail how unmaking allows designs to change over time, is an ally to sustainability and re-usability, and captures themes of "aura," emotionality, and personalization.

[1] Large portions of this chapter have previously appeared in the 2021 ACM CHI proceedings. The original citation is as follows. Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 429, 1–12 [304].

7.1 Introduction

Figure 7.1: Examples of inspirational art for unmaking. Top left: Gustav Metzger's recreation of *Public Demonstration of Auto-Destructive Art* (1960, photo by Art Damaged). Top center: Banksy's *Girl with Balloon* (2018). Top right: Yoko Ono's *Cut Piece* (1964, photo by Rob Corder). Bottom left: Survival Research Lab's *The Demanufacturing Machine* (1979, photo by SRL). Bottom right: wabi-sabi (2020, photo by Marie Lan-Nguyen).

While the dominant western narrative of beauty when it comes to describing physical artifacts is largely one of strength, durability, and perfect proportions, the very opposite – fragility, impermanence, and "imperfection" – has long been embraced across multiple cultures as uniquely beautiful and meaningful [323]. One of the most well-known examples of this is wabi-sabi, an ancient Japanese aesthetic rooted in Zen Buddhist philosophy that honors the beauty and authenticity of what is impermanent, incomplete, and conventionally imperfect [171]. Throughout the years, artistic movements around the world have resonated with these concepts. For instance, in 1959, Gustav Metzger founded the Auto-Destructive Art movement as a reaction to the repulsiveness of the violence and destruction witnessed during World War II [225]. Inspired by earlier avant-garde movements like Cubism and

Dadism that rejected the notion of mainstream societal values and aesthetics, Metzger argued that by allowing and forcing their art to disintegrate, artists could create powerful controversies that were a "kind of mass-therapy" – bringing destruction into consciousness and forcing the public to reckon with it – and an "educational programme" – allowing artists and spectators to form more intimate relationships with the materiality and temporality of the art. Metzger and his contemporaries successfully created public Auto-Destructive Art with acid, fire, and machines, but Metzger acknowledged that his theory was decades ahead of being able to be fully realized in practice, explicitly calling for collaboration between artists and engineers to create tools to more easily generate art that would disintegrate. While artists have remained interested in and still create art echoing Metzger's manifestos – Man Ray's *Object to Be Destroyed* (1923), Jean Tinguely's *Homage to New York* (1960), Niki de Saint Phalle's *Shooting Picture* (1961), Yoko Ono's *Cut Piece* (1964), John Baldessari's *The Cremation Project* (1970), Gordon Matt-Clark's *Splitting* (1974), Survival Research Lab's *Demanufacturing Machine* (1979), Chris Burden's *Samson* (1985), and Banksy's *Girl With Balloon* (2018), to name a few (Figure 7.1) – the technological tools that Metzger envisioned arguably have not yet been fully realized.

This chapter responds to Metzger's call, leveraging materials and technologies enabled through recent advances in design, Human-Computer Interaction (HCI), and digital fabrication. As an extension to the focus on *making* that has characterized digital fabrication research, I propose *unmaking* – a term to encapsulate the processes of destruction and decay that can and should be equally considered as part of the creative making process. Among other values that I detail in this chapter, designing for unmaking creates a unique opportunity for the designer of an object, the user, and the environment to collaboratively create "aura," a concept of uniqueness and authenticity that Walter Benjamin, perhaps prematurely, lamented the loss of in the ushering of our current "age of mechanical reproduction" [23].

Structuring this chapter accordingly, I summarize my main contributions as follows:

- Introduction of *unmaking* as an under-explored design opportunity that expands the creative process of physical design
- Framing of the foregrounding considerations of sustainability and re-usability within the field of digital fabrication through unmaking
- An unmaking vocabulary that can be operationalized within a digital fabrication – particularly 3D-printing – framework
- Demonstration of a workflow that allows makers to design and fabricate 3D-printed objects that exhibit controllable unmaking aesthetics

As the first introduction of these concepts, I focus the examples and discussion in this chapter mainly around 3D printing, an important and popular digital fabrication technology that boasts portability, low-cost options, and ease of integration with multiple materials. To show how unmaking can complement conventional making-centric fabrication workflows, I also draw on materials that are admittedly not backyard-degradable. However, unmaking as a concept can absolutely be applied to other digital fabrication techniques and other materials as well, a point that I address in the Discussion. In fact, as previously mentioned, because backyard-degradable interactive systems by nature unmake – often visibly and tangibly – in days and months, I forsee the development of backyard-degradable interactive systems ushering in an even richer exploration of unmaking than presented here.

7.2 Related Work

7.2.1 Destruction as an Aesthetic

Drawing inspiration from wabi-sabi and similar earlier philosophy, the HCI community has mused upon the artistic value that signs of destruction, such as visible damage and wear, might add to physical artifacts in recent years [332, 333]. For instance, in 2014, Ikemiya and Rosner presented *Broken Probes*, a study of the reassembly of shattered objects in a style reminiscent of kintsugi, the Japanese art of repair that highlights cracks with gold or decorative lacquer instead of concealing them [125]. Their user study suggested that reassembly gave new life to the objects, embodying narratives, acceptance of loss, and more generally the concept of time. Similarly, Zoran and Buechley embraced the idea that the signs of an object's breakage should be memorialized for its unique artisanship and story, utilizing digital fabrication techniques to reassemble broken objects with a new, hybrid aesthetic [398]. Design explorations in deliberately-created patina or "material traces" of wear have also suggested that such aesthetics are perceived favorably as signs of maturation and ways to add personal value to physical objects [95].

Destruction occurring over a longer span of time due to environmental exposure – described most often as degradation or decay in literature – has also been celebrated as an aesthetic that is unique to biological materials, especially in more recent years as researchers have sought to motivate the use of environmentally friendly media [200, 201, 196]. Along with embodying the sentiments and values already expressed, the degradation of biological materials provides novelty and also forces us to reflect upon and consciously deepen our relationship with nature.

7.2.2 Destruction as a Creative Act

In addition to the added aesthetic value that destruction can bring, existing literature suggests that the act of destruction itself can be entertaining, empowering, informative, and cathartic. Devendorf and Rosner's *3D Print Eraser* and *Melt* are speculative systems in which digital fabrication machines are used to erase or induce the destruction of material objects, with the main purpose being to create provocative performance art [64]. Other scholars have further suggested that enabling human interaction in processes related to destruction can develop additional meaning and value. Through a series of several detailed inquiries, Murer et al. proposed "un-crafting," or the hands-on disassembly of interactive artifacts that could be considered a methodical or controlled form of "destruction," as a means to gain material understanding and to inspire future designs [240, 242, 241, 239]. Also noteworthy is the concept of "counterfunctional design," a design methodology proposed by Pierce and Paulos to draw attention to and force the rethinking of certain elements of a design by "destroying" the concept of the conventional function of a device and instead creating inhibiting interfaces [264]. In other demonstrations, fabrication machines augment humans' abilities as agents of destruction. For example, Eickhoff et al.'s *Destructive Games* re-purpose fabrication machines as tools to enable games that resulted in the destruction of physical objects, such as money bills and toys, and the authors were surprised to report that 8 out of 12 of the participants in their user study said that they would play such games again [78].

Perhaps the findings of *Destructive Games* should not be so surprising, however. In 2012, Ringler and Reckter conducted an inquiry into whether humans would be tempted to destroy their robot and similarly found that the majority of their users chose to cause obvious damage to the robot and reported some sense of satisfaction in doing so, despite feeling that their actions were cruel [282]. The worldwide popularity of "Rage Rooms" – rooms filled with objects that individuals or groups pay to wreck – is a testament to what may be our inherent desire to destroy [219]. Indeed, despite its negative connotations, destruction is a central concept in psychotherapy for letting go and coping with loss, and several scholars have argued that we ought to embrace and enable the embodiment of these emotional needs in design [208, 290].

7.2.3 Role of 3D Printing in Destruction

The work that I have offered so far suggests that the argument that embodying destruction, decay, and deformation can bring unique meaning to design is itself not a new one in HCI. However, from existing literature alone, it remains unclear how to achieve or design this in a practical sense. Thus far in this chapter, I have presented prior work that uses digital fabrication machines to reassemble broken pieces [398], actively destroy objects [64, 78], and print biological materials that easily degrade [196]. Still, the possibility of digitally designing and fabricating objects that unmake in controllable or pre-defined ways *post-making* has been largely unexplored.

The approach that I take in this chapter is to leverage the power of multi-material 3D printing. For this, the findings in the world of 4D printing and shape-changing interfaces provide valuable techniques and inspiration. 4D printing is the process by which objects are fabricated in 2 or 3 dimensions but, upon exposure to a catalyst or stimulus, can change shape, color, or other material properties in a controllable manner [327, 187, 355]. The promise to help solve numerous design problems in transportation, architecture, assembly, and other applications has driven the rapid development and characterization of new materials and 4D printing techniques. One common approach for shape-shifting in particular is to take advantage of the shape-memory properties of conventional thermoplastics used in 3D printing by selectively building up stress during printing with print speed and direction. Upon heating, this stress is released in the form of a pre-determined shape change [9, 354, 353, 56, 188, 106, 211, 100]. Several researchers have also use the approach of turning to unusual materials, such as foaming agents [142] and living organisms [386], to induce complex changes in not only shape but texture, color, and other visible or tangible properties. Many other active investigations in novel "smart" materials from the field of materials science may eventually prove to be fruitful to draw upon as well [314, 187, 55, 355, 29, 57].

This is not to say, however, that unmaking is a subset of 4D printing, as the two have distinct goals. Upholding structural integrity is a theme that is prevalent throughout 4D printing literature, but it is one that unmaking challenges. Nonetheless, reading such literature through a different lens may reveal great insights for unmaking with 3D printing strategies. For example, Gu et al. present Geodesy as a 4D printing method that results in controllable shape-shifting, but they specifically avoid deformations that result in strength reduction [106]. I believe that Gu's approach of building in heat-activated shrinkage zones can be leveraged for unmaking, but to do this, we should embrace, not avoid, instability.

7.3 Unmaking and Sustainability

Sustainability, a driving motivator of this entire dissertation, is an increasingly pressing global concern that demands particular attention when discussing energy and material-intensive efforts, including physical prototyping. As discussed several times throughout this thesis, sustainability also has deep roots in HCI research. Even when not using backyard-degradable materials, it is imperative to respect and acknowledge the importance of environmental considerations when proposing new frameworks for designing with physical materials. As such, before presenting our vocabulary and workflow for unmaking, I dedicate this separate section to reflecting upon how unmaking can be an ally in the movement towards more sustainable thinking and practices.

7.3.1 Sustainable "Making"

There have been several successful and provocative demonstrations of artifacts and workflows embodying these principles with easily degradable, biological materials, such as mycelium [152, 339, 340, 367], but overall, the field has been slow to change. As previously discussed, the unique aesthetic of biological materials has been highlighted and celebrated. However, according to Lazaro Vasquez, Wang, and Vega's review of the environmental impact of physical prototyping, over one-third of physical prototyping reported in the last 5 years of CHI proceedings was still done with plastics, suggesting that more needs to be done to make the case for easily degradable materials [338]. Beyond simply appealing to makers' sense of environmental responsibility, bio-degradable and compostable materials offer arguably few advantages. PLA, which alone accounts for 25% of the prototypes Lazaro Vasquez et al. surveyed, is touted as a eco-friendly material that can compost in just 90 days. Unfortunately, in practice, much of it ends up in the landfill, where it can take up to 1000 years to decompose, because composting PLA requires specific industrial conditions that are not always accessible in a given locale. This should not be particularly unexpected, as the development of such materials for prototyping is currently driven by the perceived need to meet the same durability and mechanical properties of their conventional counterparts, inherently limiting their ability to degrade – certainly in the consumer's hands but even when considering industrial capabilities.

Grappling with the waste that results from current practices is a major challenge that plagues digital fabrication and maker culture [168, 66]. In 2007, Eli Blevis laid out several principles for design from a sustainability perspective, demanding that invention be "linked" with disposal – that is, invention should not be made without a detailed plan for the disposal of materials that will result – and that renewal and reuse be prioritized [28]. Several efforts have certainly been made regarding the latter. As part of their framework of "salvage fabrication" and bettering practices around sustainability in the makerspace, Dew et al. imagined that makers might be interested in concept of "perishable printing" – working with digital fabrication materials that are designed to decay – to raise awareness around the waste and leftovers of 3D printing [66]. At CHI 2020, Wu and Devendorf made critical strides towards eliminating waste in the realm of smart textiles altogether, presenting *Unfabricate*, an inquiry into designing smart textiles designed with disassembly and reuse as a focus [381]. The previous chapters of this thesis that describe the making of backyard-degradable interactive electronics have also presented alternative paradigms for more sustainable making.

7.3.2 Sustainable "Unmaking"

Continuing with Blevis's framework, I envision unmaking playing a critical role in promoting renewal and reuse. For materials such as PLA that are bio-based but not backyard-degradable, mechanical recycling – shredding the material into small parts to be remelted and renewed – can be energy-intensive, but it can in some cases be lower in environmental impact than composting when considering the entire life cycle of the material [53]. Aesthetics aside, creating objects that can spontaneously shred, or at least disassemble into their constituent colors and materials, is one practical way in which a designer can use unmaking to facilitate renewal and reuse.

Additionally, unmaking finds unique relevance in addressing Blevis's call to "link invention and disposal," which has proven somewhat more elusive than the promotion of renewal and reuse. By capturing the values surrounding ideas of destruction that have previously been identified, unmaking radically counters the conventional concepts of disposal and waste themselves, turning the process of disposal into one of continual invention. Our vision is that drawing researchers to the space of unmaking will further sustainability agendas, incentivizing the search and development of novel materials designed specially for unmaking – ones that can be degraded by an individual upon demand without reliance on energy-intensive processes and are "eco-friendly" in a truer sense than materials available today.

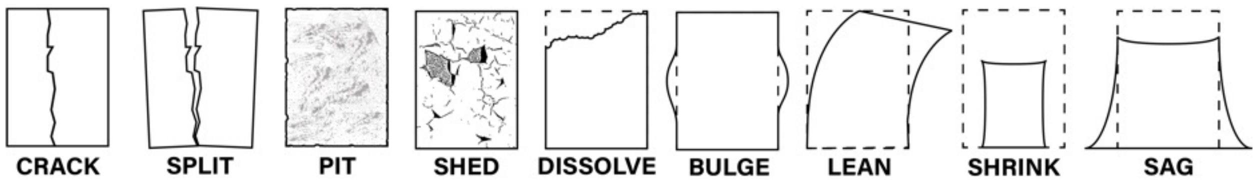


Figure 7.2: Visual icons representing selected elements of the unmaking design language

Finally, while sustainability is an important theme that is enabled and supported by unmaking, unmaking as a concept itself has valuable design, aesthetic, and philosophical implications alone, even within the limitations of currently available materials [287, 307].

7.4 The Design Vocabulary of Unmaking

Once one accepts that designing for unmaking is a worthwhile pursuit, it is natural to wonder what the space of unmaking actually looks like and how to harness known digital fabrication materials and tools. Currently, in the world of three-dimensional modeling, software design tools offer atomic operations such as extrude, loft, and revolve. As more practitioners begin to embrace unmaking within their designs, a new set of "unmaking" operations will be needed. The power of unmaking is not in a naive view of reckless destruction but in the poetic way in which a designer creates and layers the unmaking experience within an object.

I propose an initial set of expanded design vocabulary for unmaking, drawing upon aesthetics expressed in previously-discussed art and HCI research. First, from wabi-sabi-inspired research [332, 125, 398] or "un-crafting" work [240, 242, 241, 239] in which the destruction aesthetic is characterized by clean, cleavage lines, I propose the inclusion of **crack** and **split** operations. Other work has emphasized the value of other visible signs of aging and use, such as surface nicks or rusting [95, 200, 201]; for these, I offer **pit** and **shed** unmaking operations. Biological materials, which are especially attractive choices for sustainable unmaking, tend to destruct by dissociation or disintegration [196], so I propose that the **dissolve** operation be included to capture this aesthetic. Biological and water-based materials are also susceptible to warpage in response to environmental factors such as temperature and humidity [196], so operations such as **bulge**, **lean**, **shrink**, and **sag** should also be represented in an initial vocabulary set.

To summarize, I list and define these operations for designers to begin to craft their unmaking as follows:

- *CRACK* – to break without complete separation
- *SPLIT* – to completely separate into distinct pieces
- *PIT* – to undergo the formation of small pits on exterior surfaces, creating a patina of corrosion or textured indentations

- *SHED* – to undergo the removal or molting of a surface layer or outer covering
- *DISSOLVE* – to separate into atomic component parts and disintegrate
- *BULGE* – to swell or bend outward from exterior surfaces
- *LEAN* – to bend in a particular direction (typically vertically)
- *SHRINK* – to decrease or contract in size or volume
- *SAG* – to sink or bend downward from weight or pressure

This vocabulary is illustrated in Figure 7.2. This is only a starting set of essential unmaking operations; it is by no means a complete vocabulary. With some unmaking operations now defined, I next detail the technical parameters of various unmaking processes, demonstrate the vocabulary within CAD modeling software, and present working examples of actual resultant unmaking.

7.5 3D Printing Strategies for Unmaking

In this section, I provide a selection of 5 strategies that combine materials and techniques compatible with 3D printing to operationalize selected elements of the unmaking vocabulary. While 3D printing is not the only approach to exploring unmaking, the abilities to engineer hidden structures, deposit multiple materials on very small spatial scales, and generally execute designs with precision difficult to do by hand make it a valuable technique to create intriguing, sometimes unexpected manifestations of unmaking. I present strategies in the context of "material selection strategies" – encompassing the *single-material printing* strategy and 2 types of *multi-material printing* strategies (*overt* and *obscured*) – and "structural design strategies" – encompassing the *counter-stable mechanical design* strategy and the *triggered reactor design* strategy. These strategies may be used on their own, but the most powerful demonstrations of unmaking will likely result when they, along with other future strategies, are used in concert with one another.

7.5.1 Material Selection Strategies

One of the most intuitive ways to engineer unmaking with any digital fabrication technique is to simply use materials that naturally exhibit desired unmaking operations. Broadly speaking, 3D printing strategies can either rely on printing with a single material or printing with multiple materials. Following convention, I define a "single material" to be a single input filament (for techniques such as fused deposition modeling), resin (for techniques such as sintered laser annealing), or powder (for techniques such as powder bed fusion) to create artifacts that appear monolithic in composition on a macroscopic scale; these input media themselves may be a single chemical compound or element, or they may comprise homogeneous blends of multiple compounds on a microscopic scale. "Multi-material" printing can be achieved with 3D printers outfitted with multiple or exchangeable extruders or write-heads, allowing for different parts of an object to be made from different input materials. The *single-material printing* and *multi-material printing* design strategies for unmaking are discussed subsequently.

Figure 7.3: Demonstrations of different unmaking strategies. Top left: Single material printing: A PVA model is selectively dipped in water; water is absorbed and causes melting and splitting. Top right: Multi-material printing (obscured): A Timberfill wood-PLA composite shell is filled with mycelium spores; mycelium colonizes the shell material, softening it and drastically changing its appearance. Bottom left: Multi-material model printing (overt): A model comprising solid PLA for the body and iron-PLA composite for the head; when exposed to salt water, the head selectively rusts. Bottom right: Obscured multi-material printing + counter-stable mechanical design: A wood-PLA composite shell is filled with hydrated mung beans; the sprouting of the mung beans causes cleavage along a pre-defined weak layer in the cylinder.

7.5.1.1 Single-Material Printing

The *single-material printing* strategy uses a conventional single-material 3D printing approach with an input medium that is readily destructable or degradable. 3D printing objects with PVA, a common support material that *dissolves* in water, is an example of this approach (Figure 7.3, top left). Some other promising material candidates are biological materials, including food [195] and hydrogels comprising chitin, pectin, or other structural organic matter

[196]. With powder bed fusion, a newer printing technique, corrosion-susceptible materials such as metals are also now 3D printable [247]. Finally, some "non-optimized" plastics – that is, those without the conventional additives that improve their mechanical properties – are prone to discoloration and embrittlement when exposed to UV light, water, or certain solvents and could also be leveraged to achieve more types of *cracking*, *pitting*, or *shedding* effects.

This basic materials-centric approach can indeed produce some interesting unmaking effects. However, considering material choice alone is limiting, especially presently – that is, before the development of new materials that are optimized for unmaking. The unmaking vocabulary achievable by this approach is broad in theory but limited in practice. Identifying materials that are both compatible with digital fabrication flows and also easily degradable is currently challenging; most commercially available printable materials today are manufactured to *resist* unmaking, so unmaking using a single-material strategy can be difficult to induce, slow, or uncontrollable.

7.5.1.2 Multi-Material Printing (Overt)

Multi-material printing strategies in general rely on the use of multiple input materials (filaments, resins, powders) to design artifacts that may non-uniformly degrade upon exposure to different catalysts, creating more complex effects than can be achieved with a single material. The *overt multi-material printing* strategy in particular refers to the approach of printing different parts of an artifact with different materials such that the differences in external colors and textures, while perhaps subtle, are perceptible; a close examination of the external surfaces of the initial object *overtly* reveals the multi-material nature of the object. With this strategy, one part may rust and *shed* away while another *cracks* and *splits* into pieces upon freezing. Figure 7.3, bottom left, is one demonstration of this concept; iron-filled metal composite PLA filament (Proto-Pasta) is used to print one section of an object that selectively rusts upon exposure to salt water, while the plain PLA sections of the object remain unchanged. A multi-material approach affords a designer the ability to choreograph a multi-step, multi-catalyst unmaking process. An object might physically *split* when an intermediate part fails first, or it may become a patchwork of colors and *pitted* textures as it is subject to various elements. As is the case with *single-material printing* strategies, however, the richness of vocabulary achievable with this strategy is heavily dependent on the fundamental unmaking capabilities of the materials available.

7.5.1.3 Multi-Material Printing (Obscured)

One of the unique capabilities of 3D printing is the ability to create internal structures that are not obvious upon external examination. The *obscured multi-material printing* strategy is one in which an artifact appears to be printed from a single input material, but there are *obscured* internal chambers that are filled with a different "active material" – one that changes phase, shape, or otherwise releases energy upon exposure to a catalyst – to fracture or destruct those areas selectively. The entire object may also be a shell encapsulating a single chamber containing an active material that reacts with and transforms the shell material into an entirely new material with its own unmaking capabilities. A prototype inspired by this idea is shown in Figure 7.3, top right; a model is printed with a wood-PLA blend filament (Timberfill PLA) shell and filled with a hemp-mycelium spore blend (which can be printed as a paste [165]); with proper humidity and oxygen, the mycelium colonizes the shell material, changing its appearance and mechanical properties.

I explore another manifestation of the *obscured multi-material design* strategy in more detail in upcoming sections of this chapter. This strategy is especially useful in creating surprising and delightful unmaking experiences post-making. By modulating the geometry of internal chambers and the selection of the active material, we can design for a swath of unmaking operations, including *splitting*, *bulging*, and *leaning*. These capabilities can even be rendered such that the maker of such artifacts can be unaware of the hidden unmaking that is embedded.

7.5.2 Structural Design Strategies

In addition to the careful selection of materials used for printing, structural design strategies are also key to enabling the unmaking vocabulary. Possible strategies, discussed subsequently, include counter-stable mechanical design and triggered reactor design.

7.5.2.1 Counter-Stable Mechanical Design

Counter-stable mechanical design strategies abandon the rules of stable design from mechanical engineering and print with intentionally-created mechanical weak parts. For example, we can print layers that are especially thin or fragile, or adjust print parameters to intentionally create marginal designs. Figure 7.3, bottom right, illustrates this approach in combination with an obscured multi-material printing strategy; a Timberfill wood-PLA composite hollow cylinder is printed using a single-extruder Fused Deposition Modeling (FDM) 3D printer, and a weak layer is created by skipping a print layer in the printer's machine code. Sprouting mung beans placed inside the cylinder cause the cylinder to crack along the weak layer after a few days. *Counter-stable mechanical design* may be made overt to varying degrees. Weaknesses may be obvious to virtually anyone through the creation of external gaps in material, thin connections, or wrongly moving parts, perhaps even suggesting and inviting a particular interaction to catalyze unmaking. Alternatively, they may require the trained eye of a structural or mechanical engineer. They may also be completely obscured using, for instance, the creation of hidden, internal volumes that are unsupported, setting the stage for unmaking that may occur by random, unintentional interactions.

Using a *counter-stable mechanical design* strategy, and generally rethinking printing strategies in addition to material selection, can allow a design to transcend perceived material limitations and be used to simulate unexpected unmaking operations. 3D printing technologies enable us to engineer an object with sub-millimeter, layer-by-layer precision, so there is no reason to simply wait for the "right" materials to be developed before exploring unmaking. Plastics, a workhorse of 3D printing, are inherently soft materials that exhibits ductile failure, characterized by deformation before breakage. In addition to using materials-based strategies to enable unmaking in this this way (*sagging* or *leaning*), the *counter-stable mechanical design* strategy allows us to instead emulate brittle fracture – characterized by *cracking* and *splitting* along clean cleavage surfaces (such as the weak layer in Figure 7.3, bottom right) without noticeable deformation – that is normally only expected from non-plastic materials such as metals, ceramics, and glass.

7.5.2.2 Triggered Reactor Design

The *triggered reactor design* strategy uses a combination of chemical catalysts and mechanical design to engineer a chemical reactor that triggers unmaking upon being manipulated in a specified way or after a certain amount of time. By nature, this strategy as described is also a multi-material one. For example, baking soda and vinegar may be deposited into separate chambers within a 3D printed object and be forced to later combine, either when turned upside down by a human or when an internal dividing structure dissolves after a set amount of time. Once combined, the chemicals react to form carbon dioxide gas that builds up pressure and, after a few seconds, suddenly bursts through part of the object. By engineering how internal structures are designed, unmaking may be triggered by other specific manipulations, such as spinning, being dropped, or being squeezed. By tweaking the concentrations of chemicals used and type of reaction induced, the duration of unmaking can also be modulated from milliseconds to years. This strategy might be used to realize unmaking vocabulary such as *splitting*, *bulging*, *shrinking*, and *dissolving*.

7.6 Operationalizing Unmaking

I operationalize the concept and design vocabulary of unmaking by demonstrating its creative process, resulting artifact, and the eventual unmaking experience using a multi-material 3D printing process. I use an *obscured multi-material design* strategy to print chambers of an active material within a primary material, demonstrating that by varying the geometry and placement of the chambers and conditions of unmaking, I can induce different, *controllable* unmaking effects, exemplifying *splitting* and *bulging* in particular. Controllability is an important characteristic of unmaking, as we are interested not in simply "blowing things up" but rather in how designers can "build in" desired unmaking parameters into their designs. Of course, we should embrace elements of chance and entropy as well and allow for some variation in the timing and precise geometry of unmaking. I present my exemplar system not as an ideal example that embodies all of the aforementioned potential of unmaking design but rather as one that, despite being limited by current material sets, provides a preview into what can be achieved.

7.6.1 Materials

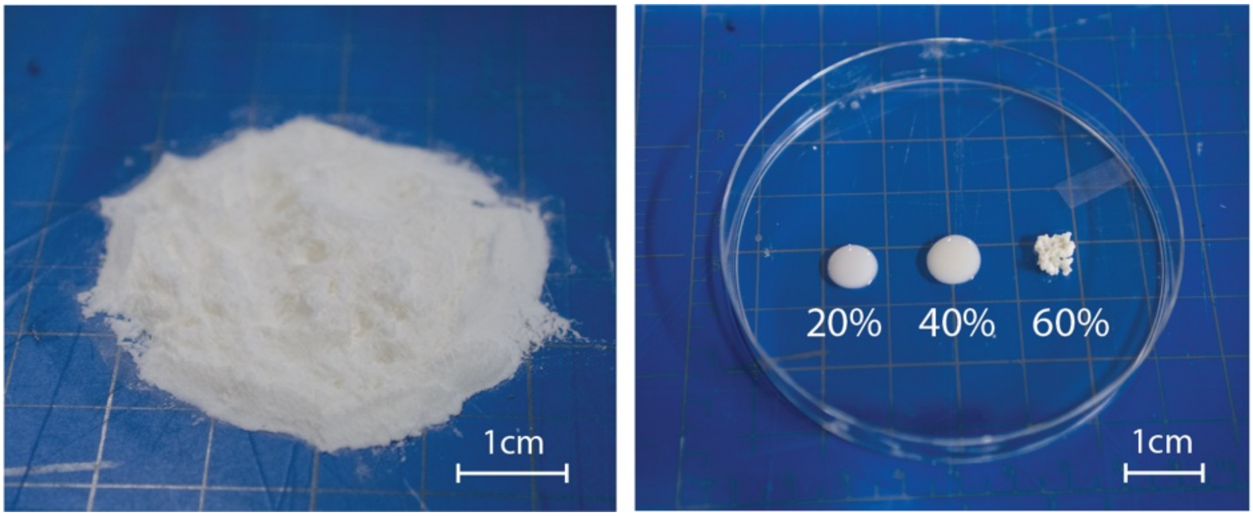


Figure 7.4: Left: dry microsphere powder. Right: prepared 20, 40, and 60 wt% water-based slurries

For this demonstration, I use off-the-shelf materials to provide a glimpse into what is already possible from an artistic perspective, even before the development of materials particularly designed to support "unmaking." I fabricate PLA objects with selectively placed chambers filled with an active material – thermally-expanding microspheres. Thermally-expanding microspheres are composed of thermoplastic shells encapsulating a low boiling point hydrocarbon. Upon heating to a temperature within an activation window, the hydrocarbon expands while the thermoplastic shell softens, causing the microspheres to swell like balloons to up to 60 times their original volume. These microspheres are conventionally used as blowing agents in automotives, construction, packaging, and coatings to reduce weight and density. In research, they have also been used in *ExpandFab*, a 4D-printing method for fabricating expanding foam artifacts [142], and in transient electronics explorations for triggering the shattering of microchips [19]. The microspheres used for my demonstrations (Nouryon Expancel 043 DU 80) are of proprietary composition and assumed to be hazardous, but Nouryon, the provider of the microspheres and one of the world's largest manufacturers of expanding microspheres, announced in 2019 that they had developed prototypes of microspheres made from cellulose – a bio-based, readily-degradable compound that could serve the same purpose as the microspheres reported here [250].

The microspheres I use here have a diameter 16-24 μm, a starting activation temperature of 95-115°C, and a maximum temperature of 147-167°C. Different varieties of microspheres with different size and temperature ranges can be used to achieve the effects I demonstrate subsequently, but their activation temperature should not exceed the melting temperature of the main printing filament to avoid uncontrolled warpage and melting.

I prepare a slurry of microspheres by mixing them in water to make them compatible with standard paste-based extrusion methods. I print with a concentration of 40 wt%. Higher concentrations make the microsphere slurry difficult to print and result in an excess mass of expanded microspheres upon destruction. Lower concentrations may result in unintentionally incomplete unmaking effects, the obvious seepage of loose slurry from 3D prints before and during unmaking, and uneven effects over time due to a decrease in slurry volume as water evaporates. Images of the dry microspheres and prepared slurries of various concentrations are shown in Figure 7.4. Microspheres slurries of concentrations greater than 40 wt% maintain their volume over time when left undisturbed, even after the water has evaporated.

7.6.2 Splitting

One of the most important operations of unmaking that is realizable by my approach is *splitting*. Figure 7.5 shows the results of defining and printing a thin plane of microspheres inside FDM-printed PLA models. The plane of microspheres is 1 mm thick and extends nearly to the object's external surfaces, with an offset margin of 0.5 mm. After printing, the objects with various internal splitting planes appear identical. However, upon heating to 130°C for 10 minutes, the objects *split* along the defined planes. While FDM-printed objects by nature are more susceptible to breakage along print line boundaries, Figure 7.5 shows that objects may be broken against print lines as well withI method. The resulting expanded microspheres may be left as-is or cleaned off with water or a dry brush.

Practically, this method may be used to divide parts into their constituent materials or colors (Figure 7.5, bottom right), which is important to maintain renewed material quality upon recycling and reuse; layers of microspheres may be inserted at each material boundary to accomplish this. If this is the primary goal, a designer may wish to explicitly prescribe unmaking to the makers and "users" of an artifact, as the artifact itself carries no signifiers of the affordance of unmaking. On the other hand, this method can also be used to intentionally create more mysterious, startling unmaking effects. The "obscured" aspect of this *obscured multi-material design* strategy – the fact that the unmaker has no indication of where and how the object will break until the moment it happens – contributes to the suspension, surprise, and perhaps delight that is evoked when the object is placed in an oven or on a hotplate and splits unexpectedly. In fact, because the unmaking that the designer has embedded is invisible, the object may unmake days, months, or years later. Conceptually, this is an important new design parameter – the fact that a design is not "done" simply once it is made. The intended design is only fully realized when the object's *unmaking* is manifested. The tension, anxiety, and delight embodied in this experience are a central characteristic of unmaking.

Additionally, the splitting of PLA objects appears to violate expected modes of mechanical failure that should result from "immutable" material properties. Although textbooks and material properties tables indicate that PLA breakage resulting from heat or mechanical stress occurs via ductile failure, as seen in Figure 7.5, the end result of the splitting operation

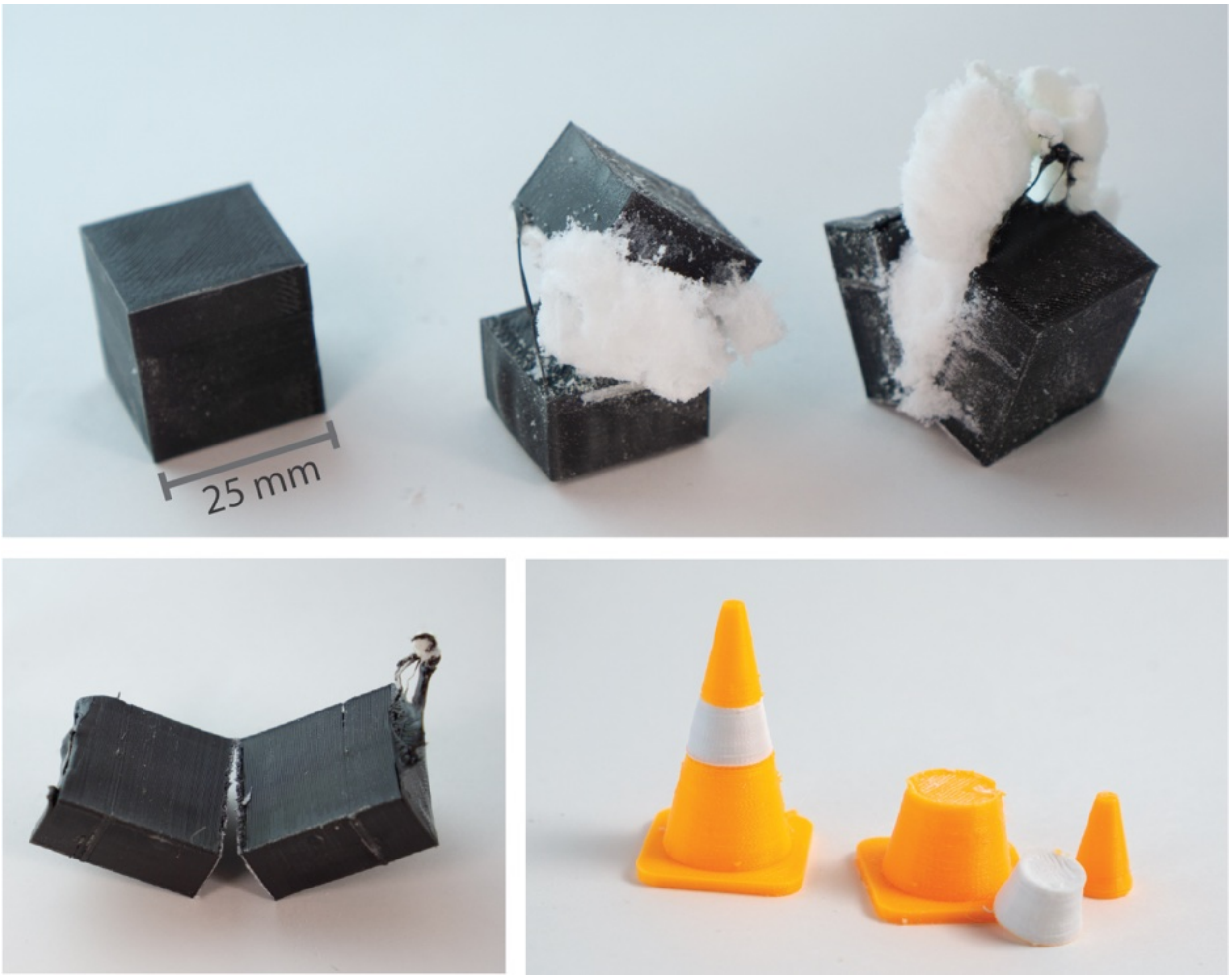


Figure 7.5: Top: PLA cubes can be split parallel to print layers OR perpendicular to print layers. Bottom left: The surfaces of the split PLA pieces after microspheres are brushed off are smooth. Bottom right: Splitting may be used to separate multi-color (or multi-material) artifacts cleanly into their constituent parts for recycling.

instead resembles brittle fracture, with slight deformation visible only on the edges of the cleavage surfaces.

7.6.3 Bulging

It may also be desirable to celebrate unmaking in an intermediate state prior to an object's separation into pieces. Much of the presented unmaking vocabulary defining various forms of deformation captures such states; here, I discuss the realization of *bulging*. With this approach, I can set the stage for highly anticipatory future unmaking experiences by inducing *bulging* in an initial unmaking experience. Like *splitting*, *bulging* can be surprising and unexpected due to the lack of outward-facing material or structural weaknesses. Upon witnessing the object bulge, an individual may halt unmaking and decide to interact with or display the deformed object for some time. Once an object has bulged, or more generally deformed (e.g. *sagged*, *leaned*, or *shrunken*), its potential for unmaking is no longer obscured. While the initial unmaking session may have evoked shock or intrigue, the subsequent session may be one of anticipation and satisfaction.

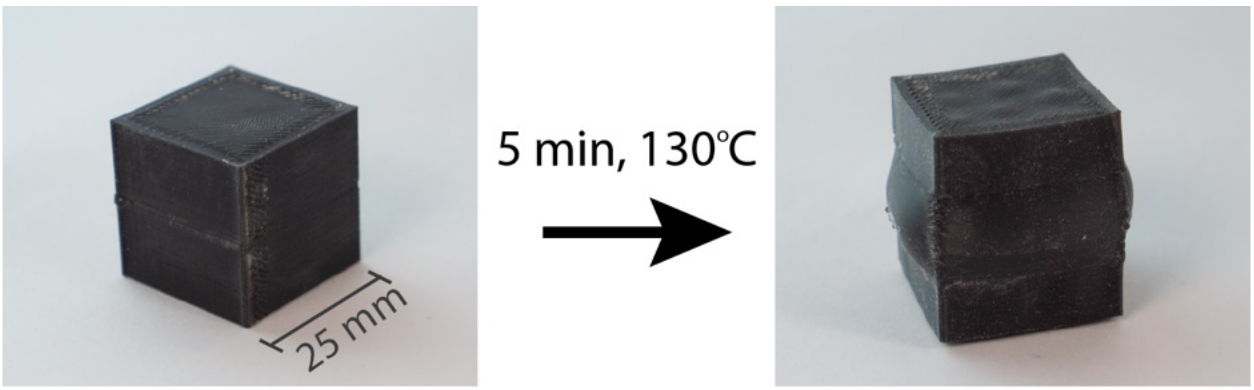


Figure 7.6: A pre-defined section of a PLA cube bulges upon heating.

To implement bulging, I define and fill larger chambers of microspheres. Figure 7.6 shows the results of defining and printing a large (24x24x5 mm inside a 25x25x25 mm cube) chamber of microspheres (40 wt% slurry). The cube was heated at 130°C for 5 minutes.

In addition to heating time, microsphere slurry concentration and heating temperature can modulate the speed and amount of bulging that happens. Figure 7.7 shows hollow PLA test pieces (15x15x10 mm with a wall thickness of 0.5 mm) (a) filled with slurries of microsphere concentrations ranging from 20% to 60% by weight and heated at 130°C for 5 minutes; and (b) filled with a 40 wt% microsphere slurry and heated to temperatures ranging from 110°C to 150°C for 5 minutes. The amount of bulging increases with heating time, heating temperature, and the concentration of microspheres used. The designer and the owner of an object (when they are different people) can thus collaboratively shape the unmaking of their objects.

7.7 3D Modeling Design Tool

Carrying out unmaking design strategies in practice can be laborious and nearly impossible if every artifact is modeled from scratch. To overcome this and support widespread unmaking design exploration, we need to develop software tools that operationalize the unmaking vocabulary. Such tools should also require as little extra input from the designer as possible to execute the details of generating printable meshes, abstracting out the mechanical and chemical know-how required to implement the designer's desired unmaking effect(s). On a

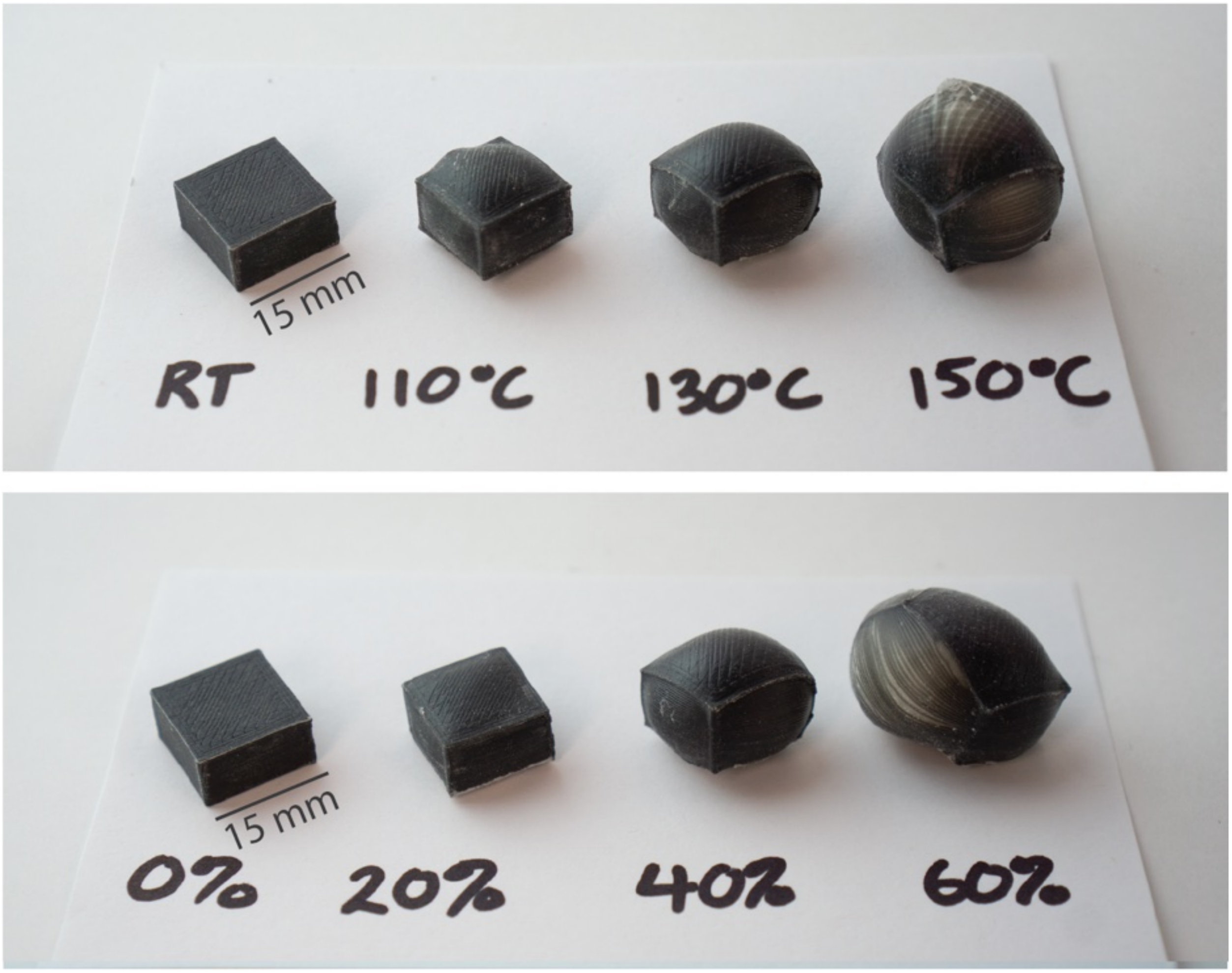


Figure 7.7: The degree of bulging may be modulated with (a) heating temperature (fixing microsphere slurry concentration at 40 wt% and heating time at 5 minutes) or (b) microsphere slurry concentration (fixing heating temperature at 130°C and heating time at 5 minutes).

high level, this involves developing an abstracted module for each unmaking operation. A designer can then can simply select desired unmaking operations from a menu to drop into their 3D models. In this section, I present example unmaking CAD macros for my PLA and microspheres system. However, this tool is not material-dependent and can be used for unmaking designs with other material combinations that use the *obscured multi-material design* recipe as well.

Users can design the unmaking of artifacts in the 3D-modeling program *Rhinoceros* (Rhino) using my custom macros. In the example shown in Figure 7.8, I demonstrate *splitting*, the unmaking operation in which an object cleaves along a specified surface. I have also made a macro for *bulging*, the effect in which an object swells in a given area

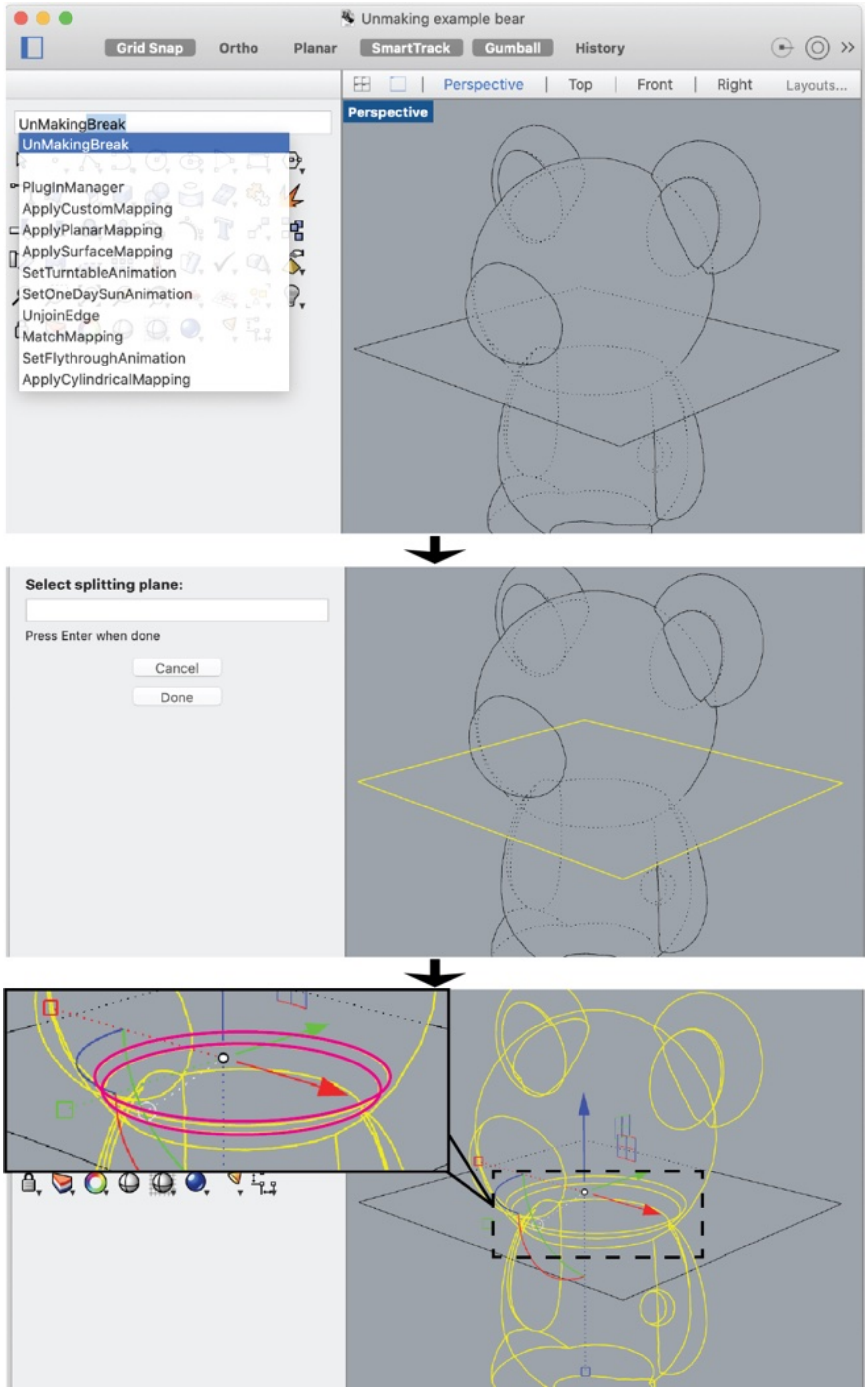


Figure 7.8: A custom *Rhino* macro allows the designer to define surfaces where a 3D model should break and generates modified meshes (pink) that can be exported as *.stl* models to be sliced, 3D printed, and unmade.

but does not physically break. The parametric macros are scripted in Rhino.Python.[2] To illustrate this, I walk through the usage of the *splitting* macro. The designer creates or loads their mesh model in Rhino and defines a surface (or surfaces) that the model should cleave along when heated. The surfaces do not have to be planar. The macro prompts the user to select these elements and automatically generates 2 printable meshes with the correct face normals: one that is the original model with a hollowed out chamber centered on the user-defined splitting surface (the chamber is 1 mm thick and 0.5 mm offset from the external surface of the model), and one that is the chamber itself (defining the microsphere volume). The resulting 3D models can then be exported as *.stl* files from Rhino to *Slic3r*, an open-source slicing program that converts the model into machine *gcode* to be interpreted by the 3D printer. The bulging macro operates in a likewise fashion, with the addition of an intermediate dialog in which the user specifies the thickness of the bulging chamber after selecting the base surface.

Such an idea can be expanded to support a greater range of unmaking operations, as well as different unmaking design strategies. For example, for *obscured multi-material designs*, we might also induce *leaning* by generating asymmetrical chambers based on a desired leaning arc that the designer draws. For *counter-functional mechanical designs*, we might take as an input a user-defined volume and convert solid parts of a model lying inside that volume to a fragile wireframe. For *triggered reactor designs*, we might use a user-defined volume to generate appropriately sized and placed U-shaped chambers, to be filled with chemicals that mix when the chambers are inverted. These designs can be chained together to create wildly creative and unexpected unmaking effects.

7.8 Fabrication Process

A wide variety of 3D printing technologies, including fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), and PolyJet 3D printing, support unmaking. In the examples of this chapter, I use a dual extruder 3D printer (modified Voxel8), with the primary extruder printing thermoplastic filament via a standard FDM process and the secondary extruder outfitted with a syringe whose flow is controlled by a peristaltic pump (Figure 7.9). PLA is printed on the primary extruder at 200°C, and the microsphere slurry is printed on the secondary extruder at room temperature.

Some of the prototypes shown in this chapter were printed on single-material 3D printers, and for these, I paused printing to hand-pipe the microsphere slurry into chamber(s) using a syringe for convenience. Virtually any deposition or extrusion-based 3D printer can be easily modified to print microsphere slurries with commercially available components and systems [397, 38].

[2] https://github.com/kwsong/unmaking_public

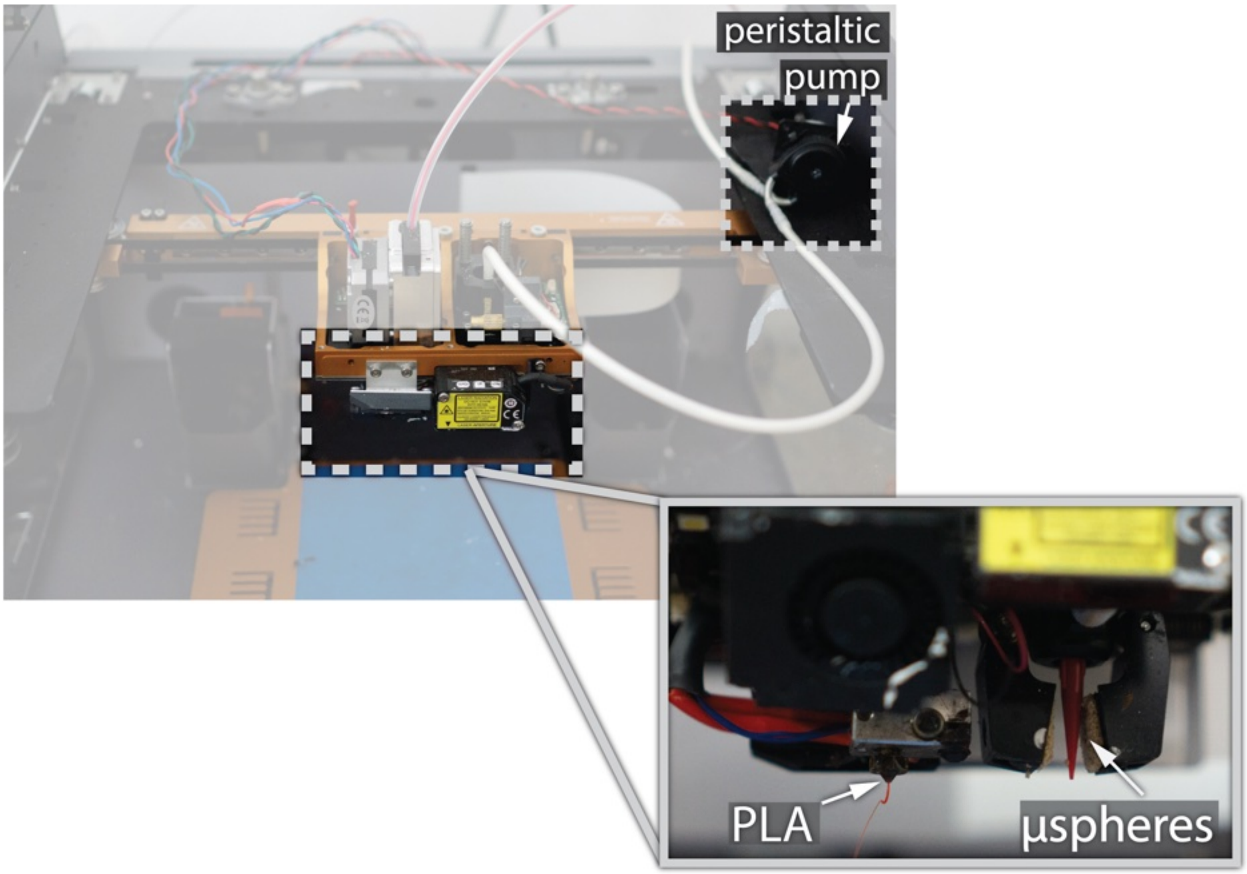


Figure 7.9: 3D printer setup with PLA printed via FDM and microspheres extruded with a peristaltic pump

7.9 Discussion

The method that I have presented is an example of an *obscured multi-material design* strategy relying on readily available off-the-shelf materials that enables surprising, and perhaps even shocking, unmaking experiences post-making. I have shown the realization of a subset of the presented unmaking vocabulary, including *splitting* and *bulging*, and am confident that future efforts will realize other operations as well. Still, it is clear that the design potential of unmaking can be most fully realized with materials specially developed with unmaking in mind. Unmaking with commercially-available thermally-expanding microspheres has its limitations. Because the activation temperature of the microspheres is relatively high, unmaking with this method requires human input; microspheres with activation temperatures as low as 80°C exist, but 80°C still exceeds most "in-the-wild" conditions.

Additionally, with regards to sustainability considerations, while this method as-is can be helpful for separating different colored PLA sections and potentially breaking PLA artifacts into small pieces for easier and higher-quality recycling, the claim of this method as "sustainable" admittedly cannot be truly realized until the microspheres are replaced with Nouryon's hopefully imminent cellulose (or equivalent) microspheres [250]. PLA must also be replaced with a material that is degradable with consumer unmaking techniques alone so that we do not rely on energy-intensive industrial recycling or composting processes. Arguably, such easily biodegradable materials are not commercially available today due to lack of compelling demand. However, I believe that a growing interest in unmaking could accelerate the development of these materials and compatible processes. One promising example of a material and technique under active investigation is Gladman et al.'s 3D printing of cellulose-based hydrogel structures with a direct-ink writing technique [314]; such structures might be seeded or filled with enzymes or bacteria that could induce selective unmaking without hazardous or excess byproducts. As previously described, I envision unmaking as a collaborative process between a designer and owner of an object that continuously creates new, personalized value in an object as it destructs and returns back to the earth, reducing the reliance on energy-intensive industrial recycling processes and potentially eliminating the concept of disposal altogether. I hope that this presentation of unmaking as an under-explored design space will increase interest in the usage of and incentivize more research and commercial development of easily degradable materials.

Still, even as presented, the unmaking concept enables and perhaps even forces designers to think about and consider how their objects should fail and destruct – something currently not often considered. My demonstrations only scratch the surface of what is possible with not only future materials but also other digital fabrication techniques, including ones that are subtractive instead of additive processes. Laser cutting and CNC milling are popular digital fabrication technologies that use a laser beam or mechanical cutter to selectively etch away parts of a starting mass of material. While *obscured multi-material* strategies are perhaps not easily adapted to such processes, the *single-material* and *counter-stable mechanical design* strategies can be readily deployed. By selecting a readily degradable material or by carving the initial material out to create mechanically weak areas, subtractive fabrication technologies can be used for unmaking in a similar way for these strategies that I have already described. I believe that designers will continue to explore and find other novel strategies for unmaking that uniquely lend themselves to particular digital fabrication technologies as well.

Next, I present 3 theoretical scenarios to illustrate what the maturation of unmaking materials and strategies could enable, especially when the PLA used in the exemplar demonstrations of this chapter is replaced by backyard-degradable materials.

7.9.1 Scenario 1: Enabling Evolving Design

A tomato plant has outgrown its small 3D-printed starter pot and is repotted, leaving the starter pot empty and unused. Fortunately, the pot was designed for unmaking. UV exposure from weeks of sitting outside has caused the pot to be broken into a collection of items, such as a saucer for the larger pot and stakes for the growing plant. As the tomato plant continues to grow and render these pieces useless, the pieces can be microwaved and broken into smaller but still usable parts. This process of creating new forms through unmaking can continue until the pieces are small enough such that they mix into and enrich the soil of the tomato plant.

7.9.2 Scenario 2: Celebrating Sustainability

A large, transparent drum teeming with a colorful potpourri of objects sits at the front of a community makerspace where the dull, black trash bins used to greet makers. Unmakers can feed their used prototypes, failed prints, partially unmade objects, or scraps into this drum. Passerbys can stop by to simply admire the colorful medley of items currently in the drum, add water to the drum and watch in delight as some objects melt away while others seemingly appear out of nowhere in front of them, heat the drum and watch other objects expand and pop, or spin the drum to observe other objects buckle and snap. Colorful bacterial colonies in the drum slowly feed on yet other objects, reducing some to pieces and giving birth to new life forms. Eventually, every object becomes compost material that is sifted into a separate tray for anyone to collect for their garden. The concept of a trash bin has transformed into one of an interactive, tangible, and living display of materials transitioning from their use to end-of-life phases.

7.9.3 Scenario 3: Creating Aura

A 3D-printed clock made decades ago by an unmaking designer in the family hangs proudly in the living room. Once a generic, circular piece placed on a desk simply to tell time, its appearance now embodies family secrets and stories. Like out of a Salvador Dalí painting, the numbers of the clock have partially melted and dripped away from the unusually hot summer 15 years ago. Orange swirls of rust adorn the face of the clock and become more vibrant and etched with each passing year. From years of jostling around in moving boxes, being misused as a frisbee, and falling off the wall, faint cracks have formed. The family has a favorite story about certain fractures that had suddenly – accompanied, as the story goes, with dramatic crackling and whistling – become accentuated a few years ago when the clock had been accidentally hung sideways for a week. These are particularly intriguing; they seem to be revealing some kind of message from a bygone generation, but one cannot be sure...not yet, anyway. The clock has long ago ceased to be able to tell time, but it has nonetheless become a one-of-a-kind family heirloom for what it represents and evokes and what it may reveal in the future.

7.10 Conclusion

This chapter presents unmaking – the destruction, decay, and deformation – of physical artifacts as a valuable extension to making. Artists and HCI researchers alike have long heralded the personal values and meanings that destruction as an aesthetic and act can bestow upon objects. Still, typically, great effort goes into ensuring that designs endure and avoid destruction. I respond to this discourse by offering an unmaking vocabulary – *crack*, *split*, *pit*, *shed*, *dissolve*, *bulge*, *lean*, *shrink*, and *sag* – for digital fabrication technologies, particularly 3D printing, to operationalize the controlled unmaking of physical artifacts. Combining material selection and structural design, I outline 5 design strategies for the unmaker: *single-material design*, *overt multi-material design*, *obscured multi-material design*, *counter-stable mechanical design*, and *triggered reactor design*. I present an *obscured multi-material design* strategy that places expanding microspheres inside PLA structures, developing an accompanying software tool to modify 3D models and demonstrating that this strategy operationalizes unexpected unmaking operations, including *splitting* and *bulging*.

Future work in unmaking includes the fulfillment of a wider array of this unmaking vocabulary through both software design tools and material explorations. Although the unmaking framework presented in this chapter can be applied in the design of any physical artifacts, the imminent realization of more backyard-degradable (i.e. easily "unmake-able") materials and interactive systems will surely better enable a deeper and wider exploration of this unmaking vocabulary and multi-stage unmaking. In return, I envision the subsequent growth in expanded realizations of unmaking fueling yet more backyard-degradable systems development, sustaining a productive cycle of making and unmaking research.

Chapter 8

Discussion

In this chapter, I discuss the limitations and future work for backyard-degradable interactive electronics.

8.1 Limitations

Future research will certainly bring a wider array of backyard-degradable interactive electronics with more advanced functionalities than presented in this dissertation, but fundamentally designing with backyard-degradable materials by nature carries limitations that require careful consideration in our designs. In this section, I discuss (1) performance limitations and how they influence future design strategies for sustainable electronics more broadly, (2) durability limitations and how they influence what applications backyard-degradable electronics may or may not be suitable for, and (3) process limitations and trade-offs regarding accessibility and mass manufacturing capabilities.

8.1.1 Performance Limitations

Working within the constraints of accessible, backyard-degradable materials inherently limits the electrical performance that we can achieve. As described in Chapter 5, *Vims* are capable of powering very low power applications on the order of a few hours to a single day, but due to their high leakage, they are not suitable for high power applications or applications that require operation over long periods of time. Performance can certainly improve with further technical development, but fundamentally, relying on DIY-friendly methods and using accessible materials results in coarse material interfaces and electrical devices that are more prone to electrical shorts, charge traps, and other defects that reduce efficiencies and energy storage capacities compared to devices produced in a controlled cleanroom environment.

Such performance limitations make the development of backyard-degradable transistors and other components for switching particularly challenging (though not impossible). This in turn means that it may be many years before we can develop a usable backyard-degradable microcontroller – the “brain” of a conventional electronic system. This dissertation has presented functional systems in spite of this current limitation; for example, by combining *Lotio* and *Vims*, we can create standalone backyard-degradable systems with two states. Still, for more advanced systems with a greater number of states, we will likely need to find ways to develop future backyard-degradable components for implementing digital logic. Meanwhile, as will be described subsequently in Section 8.2, hybrid systems that combine non-degradable microcontrollers with backyard-degradable components, such as *Vims* or *Lotio*, could be developed in parallel to research into expanding the array of individual backyard-degradable components. This will require a fundamental shift away from the current electronics design schemes dominated by digital logic to ones that support analog, more variable power sources and components that do not necessarily hold stable voltages or currents over time.

The difficulty of replacing microcontrollers makes it even more critical to pursue the systems-level design strategy of developing backyard-degradable modules but offloading power and some computation to wirelessly couple conventional electronics, as seen in Chapters 3 and 4. This strategy of course does not suit every application, but it can still be fruitful in situations where wireless power transmitters are already present or can easily be integrated into other ubiquitous and portable electronics. For this, beyond inductive chargers and ultrasound transducers, we can draw inspiration from much work in ambient RF backscattering, among other techniques for wireless power transfer [14].

8.1.2 Durability Limitations and Applications for Backyard-Degradability

Backyard-degradable interactive electronics may not be suitable for all applications, not only from a performance standpoint but also from a sustainability one. For one, as previously discussed, designing within the limitations of "safe" workflows and degradable materials comes with inherent performance trade-offs that make it difficult to imagine high-power or high-speed systems that are fully backyard-degradable. Furthermore, backyard-degradable electronics by definition are readily degradable and not durable. However, some systems are in fact intended to be used for virtually forever. It would be more sensible – and sustainable – to design such systems to be as durable as possible instead of focusing on their backyard-degradability. Creating such systems with backyard-degradable materials could potentially create a cycle of excessive fabrication and discard that in fact has an overall greater environmental impact. Backyard-degradable interfaces should not be assumed to be the most sustainable solution in all cases. Rather, the impact of materials' and devices' whole lifecycle for each application needs to taken into consideration.

8.1.3 Process Limitations and Mass Manufacturing

While I argue that prioritizing fabrication methods and materials that are accessible to the "everyday maker" is critical from a technology democratization point of view and will also surely lead to the discovery of unexpected technologies, this approach inherently limits the scalability of the resulting systems. In this thesis I have tried to use techniques that have a known pathway to mass manufacturing where possible; for example, with *Vims*, the screenprinting that is done by hand can also be done by a high-throughput industrial screenprinter. However, this is not always the case. For example, the leaf heaters of Chapter 3 rely on individual leaf skeletons, which are variable in size but inherently small. One approach for adapting those to larger scale manufacturing would be to leverage industrial techniques that can partially pulverize and make large sheets of leaves (similar to papier-mâché), or alternatively, the leaf skeleton structure can be used as a template or inspiration for growing or fabricating, via additive manufacturing, bio-inspired large-area structures with alternative, more scalable backyard-degradable materials.

8.2 Future Work

I envision that in the future, an everyday maker can order curated backyard-degradable interactive electronics toolkits – containing either a selection of pre-assembled components or a selection of raw materials for the maker to fabricate components themselves – that are paired with software design tools that assist them in ideating, designing, fabricating, and troubleshooting their very own sustainable electronics prototypes. In pursuit of such a vision, there is much work to be done. In this section, I describe future work in (1) expanding the toolbox of backyard-degradable interactive electronics components, (2) scoping and developing backyard-degradable hardware toolkits and software design tools for deployment with real makers, and (3) broadening the array of unmaking methodologies and design tools.

8.2.1 Making Backyard-Degradable Interactive Electronics

8.2.1.1 Developing New Materials, Components, and Interfaces

Of course, there is still much work to be done in terms of designing more kinds of backyard-degradable electrical systems and components beyond what is presented in Chapter 5 and 6, including power efficient mechanical actuators. To this end, it may be possible to leverage the actuators that we see in the natural world, such as twitching insect legs or rapid plant movement, to create power-efficient bio-hybrid actuators. Beyond having great potential for highly unusual aesthetics and applications, as illustrated in Figure 8.1, cockroach legs and plants that exhibit rapid plant movement, such as *Mimosa pudica*, enact very noticeable and often dramatic movement in response to an extremely small (mV-level) electrical action potential – a coveted quality for backyard-degradable electronics, which are currently performance-limited.

8.2.1.2 Interfacing with Conventional Electronics

Secondly, there are opportunities for hybrid systems that combine backyard-degradable components, such as *Vims*, with conventional electronics, like microcontrollers. This requires a

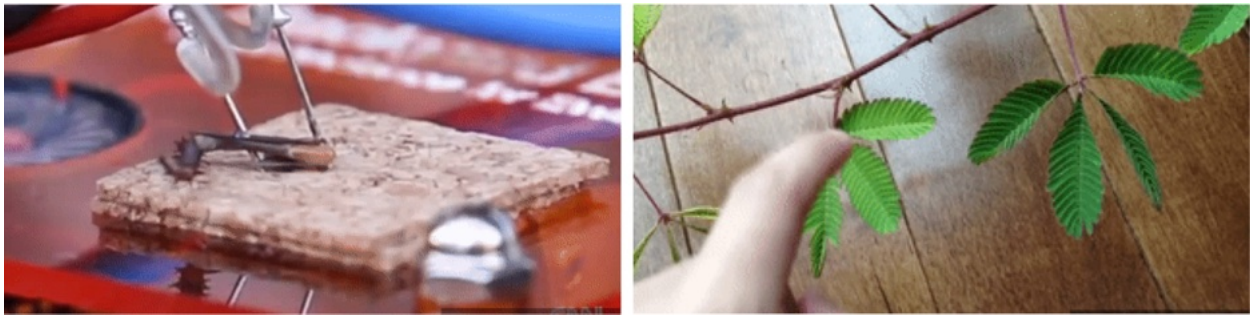


Figure 8.1: Left: a cockroach leg twitching in response to a small (mV-level) electrical pulse. Right: *Mimosa pudica* plant moving in response to touch.

paradigm shift when it comes to what electronics we use. For example, we conventionally demand that the power source for digital electronics remain above a certain threshold voltage and ideally also remain constant, but *Vims* does not match that model at all. Still, we can find uses for *Vims* by casting aside (or "unmaking") some of these conventional design rules and also of course optimizing microcontrollers to consume as little power as possible. The outputs of future projects in this domain are new flavors of design rules and strategies and also potentially reincorporating some analog-based schemes that have largely fallen out of fashion in recent decades. While hybrid systems would require degradable and non-degradable parts to be separated at end of life, they could be valuable in the more widespread transition to a wider array of fully backyard-degradable interactive electronics, providing the opportunity to test and refine how individual backyard-degradable components work in a system, both in terms of electrical and mechanical performance and in terms of user experience (with real designers and users). This approach draws inspiration from hybrid cars, which have proven themselves to be valuable not only in their own right from a consumer's point of view but also as a transitional technological platform for deploying and developing individual electrical components that gone on to find use in fully electric vehicles.

8.2.1.3 Leveraging Artificial Intelligence and Machine Learning

Within the umbrella of making but with a very different skill set, there is also an opportunity to develop software tools that help HCI and design researchers find insights from materials science and engineering literature that have the potential to be translated into accessible fabrication environments. This builds on existing work, such as the ScholarPhi project at Berkeley, UW, and the Allen Institute for AI that produced several tools for helping readers of complex technical papers understand formulas and annotate those papers [1]. In the context of backyard-degradable interactive electronics, to provide an illusrative example: it may be desirable to utilize the findings from a chemistry or biology paper, which describes ball grinding a mixture of ingredients at a highly specific temperature and pressure with a

[1] https://scholarphi.org/

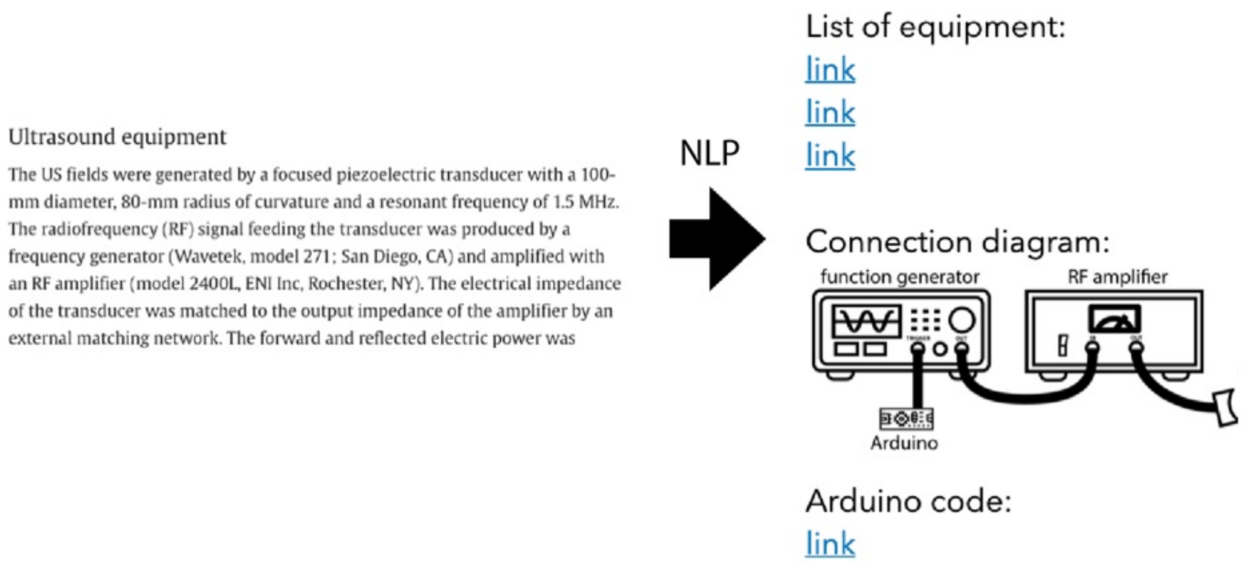


Figure 8.2: Envisioned future software systems may leverage NLP techniques to translate complex methods sections of domain-specific papers into more accessible, Instructables-like pages for HCI and design researchers to use.

certain amount of vigor. However, it may possible that 80% of the impressive result could be achieved by simply mixing the components with a wooden craft stick. An example of a project that I imagine is illustrated in Figure 8.2. It draws upon similar Natural Language Processing (NLP) techniques to the ScholarPhi project but takes a complex methods section from an engineering paper and generates an Instructables-like page that simply consists of links to equipment to buy (ideally lower-cost version when available) and any relevant instructions or code that an HCI researcher or even hobbyist maker can use as a starting point for testing and prototyping.

8.2.2 Designing Toolkits for the "Everyday Maker"

As discussed in the Section 8.1 (Limitations), it will be valuable to consider how backyard-degradable interactive systems may be adapted for larger-scale manufacturing and distribution. However, meanwhile, there is still much future work to be done regarding the deployment of development toolkits for backyard-degradable interactive systems to the maker community. As discussed in Chapter 2, developing technologies for and with the maker community can be extremely valuable in uncovering unexpected applications and directions for future research and products.

This dissertation has focused on the development of backyard-degradable technologies that, in theory, utilize accessible materials and workflows. Future work shall put this assumption in practice, utilizing participatory design workshops with backyard-degradable kits to understand the challenges, desires, and design processes of real maker communities. To this point, I have referred to the "maker community" as a coherent group, but in reality makers span many spectra, including access to resources, electronics experience, presence and impact of mental or physical disabilities, and education level. Makers also include sub-communities of people in different geographical regions, as well as groups that underrepresented in the technology development process. Future work thus needs to be cognizant of these various spectra and should separately study and forefront the visions of different groups, developing tools that are catered towards their visions, working styles, and limitations.

8.2.2.1 Participatory Design Workshops

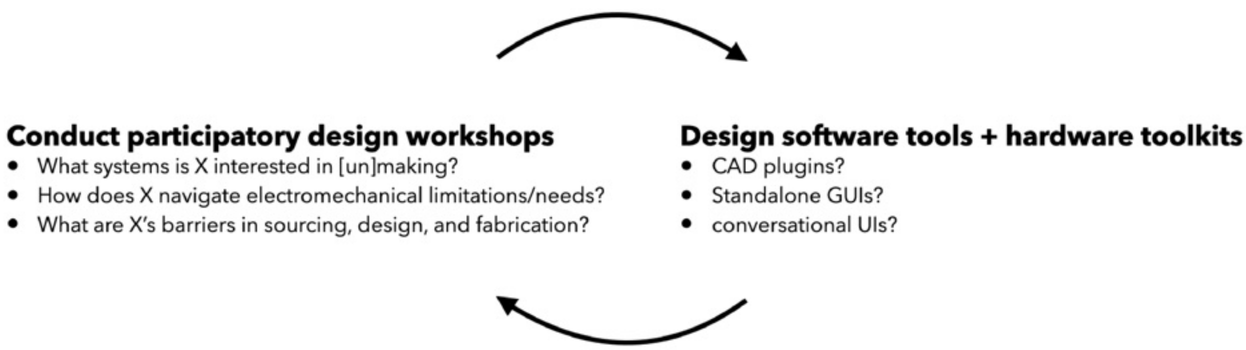


Figure 8.3: Future work to enable the "everyday maker" will comprise iterative cycles of participatory design workshops and the development of software design tools and hardware toolkits.

Illustrated in Figure 8.3, I see this line of future work as an iterative process, cycling between such participatory design workshops and the development of hardware toolkits and software design tools customized for each maker population, and perhaps even each application. As a starting point, I plan to hold workshops with engineering students and hobbyists with a non-zero amount of electronics prototyping experience. Such workshops would center around tasks that ask participants to design systems, perhaps hybrid ones with both backyard-degradable and non-degradable parts, to generate an array of applications for which backyard-degradable components can find use. In addition to better understanding the visions and needs of makers with an electronics background specifically, such workshops would be invaluable in understanding what materials and components should be pre-made, what example systems could be provided as inspiration, and what software (e.g. starter code for microcontrollers) would be useful in workshops with populations with a less extensive electronics background.

From there, there are many possible groups of "everyday makers" that I envision could benefit from backyard-degradable interactive electronics toolkits and could also help us generate new ideas for future research. For example, in medicine, there are many electronic components that are designed to be single-use, such as electrodes for electrocardiograms, thermometer tips, and breast pump parts. In rural or remote environments, these components are not only particularly difficult to dispose of but are also sometimes not available. Developing toolkits with and for medical professionals in such environments could not only help create ecosystems of medical devices that are not only eco-friendly but also help fill a currently unfulfilled need for critical components.

Alternatively, workshops with artisans in different locales could help us discover new sets of backyard-degradable materials with unique capabilities that ones that are more familiar to us do not have. For example, in the CHI2024 workshop on sustainable unmaking [307], the Hawaiian artist Corinne Okada Takara[2] shared an array of native Hawaiian plants and organisms that exhibited shape changes, underwent unusual visual effects as they decayed, and could be used for bioremediation. While Indigenous Hawaiian artists have been using these materials in their practice for centuries, such materials were unknown to virtually all of the 30 participants of the workshop. Introducing backyard-degradable electronics components to these artists and working with them to blend their material knowledge with ours could indeed be fruitful as we continue to build the toolbox of backyard-degradable electronic components.

8.2.2.2 Design Tools

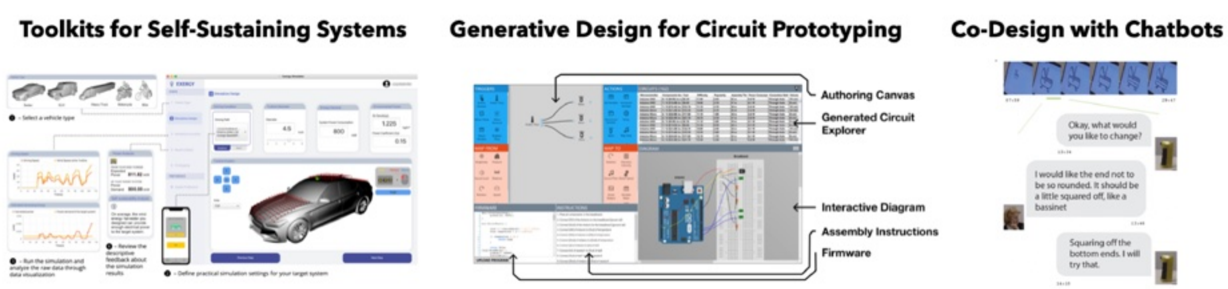


Figure 8.4: Screenshots of software tools for designing hardware. From left to right: Exergy [258], Trigger-Action Circuits [10], and a chatbot for designing laser-cut objects [54].

An important outcome of participatory design workshops is the development of software design tools that can help makers design and fabricate backyard-degradable interactive electronics on their own, beyond the supported environment of workshops. Software tools for designing hardware are the focus of a rich body of research in HCI [258, 10, 193]. As illustrated in Figure 8.4, there are stand-alone custom graphical user interfaces, such as Exergy, which is a toolkit for designing wind-powered vehicles [258]. Trigger-Action Circuits is another software for hardware prototyping that takes desired behavioral inputs and generates assembly instructions for circuits that can achieve that behavior [10]. It generates

[2] https://www.okadadesign.com/

microcontroller firmware, and it creates assembly instructions to guide the user through the construction process.

One potentially promising avenue of design tools leverages recent advancements in LLMs and chatbots. Cuadra et al. presented a tool that allows humans to co-design laser-cut ornaments w/ a conversational user interface [54]. Designing with emerging technologies like *Vims*, Lotio, and future backyard-degradable components is an open ended endeavour, and there is likely untapped potential to use generative AI to help people not only envision novel applications but also work through and understand the limitations of backyard-degradable technologies given their individual background.

8.2.3 Unmaking

One area of future work that falls naturally from Chapter 7 is to operationalize and explore a broader unmaking vocabulary for the design of backyard-degradable interactive electronics specifically. For instance, materials may be selected to degrade sequentially, influencing electronic functionality along the way.

Moreover, unmaking is a non-linear process that may involve smaller cycles of repairing, upgrading, and re-making as a system ages. When something breaks, it may be desirable to repair it to prolong their initial function. However, instead of trying to restore it to its original pristine condition, which can be extremely difficult, we might want to embrace imperfection as an opportunity to customize and personalize an object; such a sentiment is evident in the popular practice of patching holes in denim with colorful, non-denim decorations. Here I see an opportunity to leverage the recent advances in generative AI to give us ideas for repair, given the limited resources we have and also some aesthetic inspiration as input. We might imagine creating a software tool, illustrated in Figure 8.5, that takes as input images of a broken object, a mood board for inspiration, and a list available resources, and as output

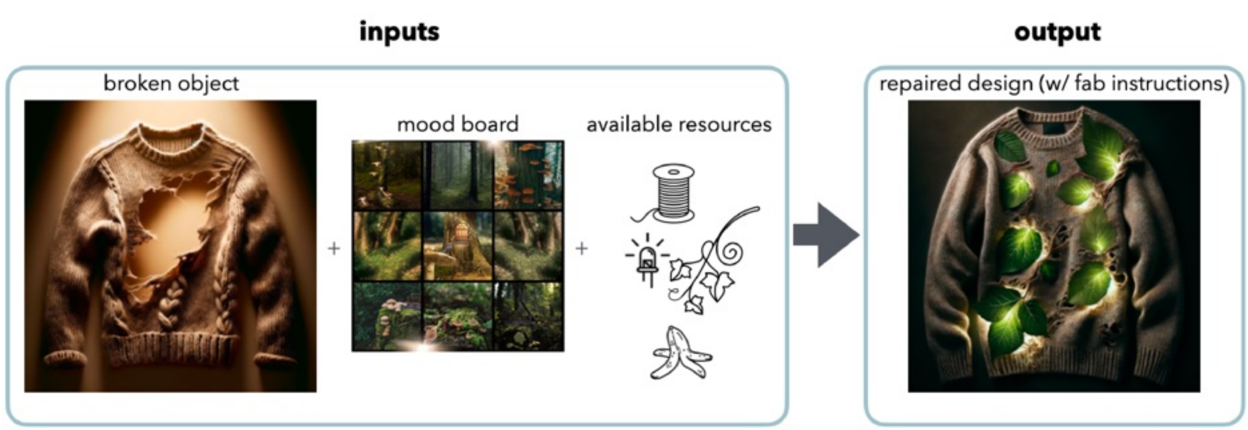


Figure 8.5: An envisioned tool for salvage repair takes an image of a broken object, aesthetic inspiration, and a list of available resources as input and outputs ideas (and instructions) for repair.

offers the user a design, which the user can iterate upon, and instruction sheet for how to repair that object. Depending on the object, there may even be opportunities to directly output machine code to accomplish the repair with 3D printing, machine knitting or other digital fabrication tool. This builds on an existing tradition within HCI of creatively reusing, repairing, and remaking, physical resources, such as electronic waste [162].

Chapter 7 drew inspiration from published work in worn design, more-than-human design, and auto-destructive art to propose an initial unmaking vocabulary and framework, but moving forward, there are also many opportunities to collaborate with architects and urban planners, transient electronicists, artists, knitters, and other communities who might be interested in incorporating some flavor of unmaking into their work for sustainability, political protest, security, and novel aesthetics, among others.

8.3 Outlook

In the future, I hope to see software design tools that assist makers in making, re-making, and un-making their own backyard-degradable interactive electronics with the materials available around them from scratch, along with varieties of commercially available hardware toolkits that provide a starting point for makers to explore creating their own sustainable electronics. In addition, backyard-degradable electronics toolkits could serve as a low-cost, accessible educational tool for use in classrooms to help students of various ages explore electronics, sustainable materials, and the relationship between the two. Makers with no prior knowledge about the layers needed to make a supercapacitor would certainly gain a more intimate understanding and appreciation for the requirements, capabilities, and involved resources in the manufacturing of supercapacitors by constructing *Vims* with their own hands. Simultaneously, partaking in such an activity could also spur novel ideas for variations and use cases that other makers more entrenched in the protocols of the development of conventional electronics would not forsee. In this way, I envision backyard-degradable interactive electronics inviting mass participation and empowering diverse communities of everyday makers to participate in and also steer the development of future sustainable electronics systems.

Chapter 9

Conclusion

Although there is much interest around the development of sustainable interactive systems, today, we largely lack the materials, fabrication strategies, and design tools that we need to realize such systems. This dissertation contributes design strategies, materials, and tools to make – and unmake – backyard-degradable interactive electronics with accessible and easily degradable materials. In summary, it offers three contributions:

1. a systems-level design strategy for making backyard-degradable electronics that leverages wireless energy transfer,
2. a complementary design strategy for making backyard-degradable electronics that whereby I build individual backyard-degradable components that can come together to form standalone systems, and
3. a design strategy and framework for unmaking, a design opportunity supported by the use of backyard-degradable materials, that we can "build into" physical systems at the time of initial conception.

The first two contributions seek to answer the question, *How can we make backyard-degradable interactive electronics?* I have presented backyard-degradable modules that are wirelessly activated by non-degradable electronics, a systems-level design strategy that allows us to explore the capabilities and applications of backyard-degradable interactive electronics while we develop and optimize backyard-degradable power solutions. The *leaf-based heaters* of Chapter 3 can be integrated into paper packaging and activated by inductive chargers to wirelessly heat the packaging's contents. They are low cost, can be made with widely available ingredients, seamlessly blend into a flat form factor, and offer the option of unique aesthetics. *Füpop*, described in Chapter 4, is a system whereby fully edible liquid food pouches inside the mouth can be wirelessly "popped" by a focused ultrasound transducer outside the cheek to deliver choreographed flavor experiences. By separating the edible, backyard-degradable component from the power transmitter, it for the first time achieves a human-food interface that does not require the mouth to remain partially open to accommodate wires or tubes.

This thesis also works towards the development of a toolkit of individual components that can be combined for standalone backyard-degradable interactive electronics. *Vims*, described in Chapter 5, are backyard-degradable electrical energy sources that can replace batteries in certain low power and temporary applications. In addition to serving as a more sustainable alternative to batteries, *Vims* can be made with a variety of materials and are highly customizable in terms of shape and geometry. With *Vims*, electrical power thus becomes a first-class design element that is not merely "designed around" at the last minute. *Lotio*, described in Chapter 6, is an example of a backyard-degradable display that can be integrated with existing wearables or used in conjunction with *Vims*. Working within the constraints of currently accessible and backyard-degradable materials inspired the use of lotion as an electronically active material and mediator for a novel kind of skin-worn display.

The third contributions seeks to answer the question, *How can we unmake backyard-degradable interactive electronics?* I have presented *unmaking* in Chapter 7 as a design opportunity for extending the life of backyard-degradable interfaces, and tangible artifacts more generally, beyond their initially intended use case(s). As discussed in Chapter 7, unmaking may be considered even when we do not use backyard-degradable materials. However, backyard-degradable materials, being inherently unmake-able, certainly make exploring unmaking more accessible, so I envision that as we explore more backyard-degradable materials and electronics, the aesthetic and functional possibilities for unmaking will also grow.

Finally, as a whole, this dissertation explores the question, *How can the practice of designing backyard-degradable interactive electronics be a constructive one?*, or, more simply, *Why make backyard-degradable interactive electronics*? The most straightforward answer to this question – one that has been discussed extensively in this thesis – is that backyard-degradable interactive electronics provide sustainable alternatives to conventional parts that are accessible to makers with a wide array of resource availabilities and electronics experience. However, in addition, I have argued that designing backyard-degradable interactive electronics can and should be more than just about imitating or replacing conventional ones, because backyard-degradable materials possess unique features and capabilities in their own right.

This philosophy is not new to HCI. In fact, in their seminal 1992 CHI paper that has been cited nearly 1000 times since publication, "Beyond Being There," Jim Hollan and Scott Stornetta argued that new telecommunication technologies that imitated face-to-face communication would always fall short of that which they imitated; rather, new technologies should *go beyond* physical proximity (i.e. "being there"), leveraging instead the unique features of the technologies inherently absent in face-to-face communication. Drawing inspiration from such philosophy and bringing it into a very different context, in this dissertation, while backyard-degradability began as a constraint to encourage the selection of materials with small carbon footprints, it also emerged as a *constructive* aspect of the design process – one that led to systems with aesthetics, interaction modalities, and design possibilities not afforded by their non-degradable counterparts. In this way, I pose backyard-degradable interactive electronics not merely as more sustainable drop-in replacements for conventional, non-degradable electronics but rather as a technology that can *go beyond* traditional electronics, offering options for creativity that designers may voluntarily select even when higher-performance, more durable electronic components are readily available.

While tackling the looming climate crisis that we face certainly requires coordinated and widespread cooperation on the part of local and national governments, as well as global alliances, individual actions and innovations, even if they begin small, are critical. My vision for the work in this dissertation integrates materials science innovations, electrical engineering, software development, and of course real people to develop backyard-degradable interactive electronics and bring them into the hands of the everyday maker, providing one path for a creative, more sustainable future that we can all play our part in building.

Bibliography

[1] S. Abdalla and A. A. Al-Ghamdi. "Electrical energy from foods". In: *Journal of Renewable and Sustainable Energy* 3.6 (2011), p. 063106. DOI: 10.1063/1.3659289.

[2] Xavier Aeby et al. "Fully 3D Printed and Disposable Paper Supercapacitors". In: *Advanced Materials* 33.26 (2021), p. 2101328. DOI: https://doi.org/10.1002/adma.202101328.

[3] United States Environmental Protection Agency. *An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling*. July 2021.

[4] United States Environmental Protection Agency. *National Overview: Facts and Figures on Materials, Wastes and Recycling*. United States Environmental Protection Agency. 2020. URL: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling.

[5] Ismo Alakärppä et al. "BreathScreen: Design and Evaluation of an Ephemeral UI". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 4424–4429. DOI: 10.1145/3025453.3025973.

[6] Ferran Altarriba Bertran et al. "Making Sense of Human-Food Interaction". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300908.

[7] Ferran Altarriba Bertran et al. "Making Sense of Human-Food Interaction". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300908.

[8] Ferran Altarriba Bertran et al. "The Playful Potential of Shared Mealtime: A Speculative Catalog of Playful Technologies for Day-to-Day Social Eating Experiences". In: *Proc. ACM Hum.-Comput. Interact.* 5.CHI PLAY (Oct. 2021). DOI: 10.1145/3474694.

[9] Byoungkwon An et al. "Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces". en. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. Montreal QC, Canada: ACM Press, 2018, pp. 1–12. DOI: 10.1145/3173574.3173834.

[10] Fraser Anderson, Tovi Grossman, and George Fitzmaurice. "Trigger-Action-Circuits: Leveraging Generative Design to Enable Novices to Design and Build Circuitry". In: *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. UIST '17. Québec City, QC, Canada: Association for Computing Machinery, 2017, pp. 331–342. DOI: 10.1145/3126594.3126637.

[11] Peter Andersson et al. "Printable all-organic electrochromic active-matrix displays". In: *Advanced Functional Materials* 17.16 (2007), pp. 3074–3082.

[12] María R. Ansorena, Norma E. Marcovich, and Mariana Pereda. "Food Biopackaging Based on Chitosan". en. In: *Handbook of Ecomaterials*. Ed. by Leticia Myriam Torres Martínez, Oxana Vasilievna Kharissova, and Boris Ildusovich Kharisov. Cham: Springer International Publishing, 2018, pp. 1–27. DOI: 10.1007/978-3-319-48281-1_68-1.

[13] Nivedita Arora and Gregory D. Abowd. "ZEUSSS: Zero Energy Ubiquitous Sound Sensing Surface Leveraging Triboelectric Nanogenerator and Analog Backscatter Communication". In: *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*. UIST '18 Adjunct. Berlin, Germany: Association for Computing Machinery, 2018, pp. 81–83. DOI: 10.1145/3266037.3266108.

[14] Nivedita Arora et al. "MARS: Nano-Power Battery-Free Wireless Interfaces for Touch, Swipe and Speech Input". In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1305–1325. DOI: 10.1145/3472749.3474823.

[15] Nivedita Arora et al. "SATURN: A Thin and Flexible Self-Powered Microphone Leveraging Triboelectric Nanogenerator". In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2.2 (July 2018). DOI: 10.1145/3214263.

[16] Vicente Arroyos et al. "A Tale of Two Mice: Sustainable Electronics Design and Prototyping". In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491101.3519823.

[17] Akash Badshah et al. "Interactive Generator: A Self-Powered Haptic Feedback Device". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 2051–2054. DOI: 10.1145/1978942.1979240.

[18] Tim Bajarin. *Why the Maker Movement Is Important to America's Future*. 2014. URL: https://time.com/104210/maker-faire-maker-movement/.

[19] N. Banerjee et al. "From chips to dust: The MEMS shatter secure chip". en. In: *2014 IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS)*. San Francisco, CA, USA: IEEE, Jan. 2014, pp. 1123–1126. DOI: 10.1109/MEMSYS.2014.6765843.

[20] Leslie Baumann. "Understanding and treating various skin types: the Baumann Skin Type Indicator". In: *Dermatologic clinics* 26.3 (2008), pp. 359–373.

[21] Fiona Bell, Netta Ofer, and Mirela Alistar. "ReClaym Our Compost: Biodegradable Clay for Intimate Making". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3517711.

[22] Fiona Bell et al. "Designing with Alganyl". In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '22. Daejeon, Republic of Korea: Association for Computing Machinery, 2022. DOI: 10.1145/3490149.3501308.

[23] Walter Benjamin. *The Work of Art in the Age of Mechanical Reproduction, 1936*. 1935.

[24] Jane Bennett. *Vibrant Matter: A Political Ecology of Things*. Durham, NC, USA: Duke University Press, 2010.

[25] C. Betancourt-Aguilar et al. "Glycerin as byproduct of biodiesel production, its characteristics, applications and soil use." In: *Cultivos Tropicales* 37.3 (2016), pp. 7–14.

[26] Dinesh Bharadia et al. "BackFi: High Throughput WiFi Backscatter". In: *Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication*. SIGCOMM '15. London, United Kingdom: Association for Computing Machinery, 2015, pp. 283–296. DOI: 10.1145/2785956.2787490.

[27] Sanket Bhoyate et al. "Eco-Friendly and High Performance Supercapacitors for Elevated Temperature Applications Using Recycled Tea Leaves". In: *Global Challenges* 1.8 (2017), p. 1700063. DOI: https://doi.org/10.1002/gch2.201700063.

[28] Eli Blevis. "Sustainable interaction design: invention & disposal, renewal & reuse". en. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '07*. San Jose, California, USA: ACM Press, 2007, pp. 503–512. DOI: 10.1145/1240624.1240705.

[29] J. William Boley et al. "Shape-shifting structured lattices via multimaterial 4D printing". en. In: *Proceedings of the National Academy of Sciences* 116.42 (Oct. 2019), pp. 20856–20862. DOI: 10.1073/pnas.1908806116.

[30] Jas Brooks, Noor Amin, and Pedro Lopes. "Taste Retargeting via Chemical Taste Modulators". In: *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. UIST '23. ¡conf-loc¿, ¡city¿San Francisco¡/city¿, ¡state¿CA¡/state¿, ¡country¿USA¡/country¿, ¡/conf-loc¿: Association for Computing Machinery, 2023. DOI: 10.1145/3586183.3606818.

[31] Robin Gordon Brown and James Ladyman. "History of materialism". In: (2020). DOI: 10.4324/9780415249126-DC122-1.

[32] Merijn Bruijnes, Gijs Huisman, and Dirk Heylen. "Tasty Tech: Human-Food Interaction and Multimodal Interfaces". In: *Proceedings of the 1st Workshop on Multi-Sensorial Approaches to Human-Food Interaction*. MHFI '16. Tokyo, Japan: Association for Computing Machinery, 2016. DOI: 10.1145/3007577.3007581.

[33] Hronn Brynjarsdottir et al. "Sustainably unpersuaded: how persuasion narrows our vision of sustainability". en. In: *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. Austin, Texas, USA: ACM Press, 2012, p. 947. DOI: 10.1145/2207676.2208539.

[34] Leah Buechley and Michael Eisenberg. "The LilyPad Arduino: Toward Wearable Engineering for Everyone". In: *IEEE Pervasive Computing* 7.2 (2008), pp. 12–15. DOI: 10.1109/MPRV.2008.38.

[35] Leah Buechley, Sue Hendrix, and Mike Eisenberg. "Paints, Paper, and Programs: First Steps toward the Computational Sketchbook". In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. TEI '09. Cambridge, United Kingdom: Association for Computing Machinery, 2009, pp. 9–12. DOI: 10.1145/1517664.1517670.

[36] Leah Buechley and Benjamin Mako Hill. "LilyPad in the Wild: How Hardware's Long Tail is Supporting New Engineering and Design Communities". In: *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. DIS '10. Aarhus, Denmark: Association for Computing Machinery, 2010, pp. 199–207. DOI: 10.1145/1858171.1858206.

[37] Leah Buechley and Hannah Perner-Wilson. "Crafting Technology: Reimagining the Processes, Materials, and Cultures of Electronics". In: *ACM Trans. Comput.-Hum. Interact.* 19.3 (Oct. 2012). DOI: 10.1145/2362364.2362369.

[38] byFlow. *3D Food Printer*. https://www.3dbyflow.com. Accessed: 2020-09-10. 2020.

[39] Serena Camere and Elvin Karana. "Fabricating materials from living organisms: An emerging design practice". In: *Journal of Cleaner Production* 186 (2018), pp. 570–584. DOI: https://doi.org/10.1016/j.jclepro.2018.03.081.

[40] Mengyu Cao. "Lunhui: Upcycled Creations". In: *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition*. C&C '17. Singapore, Singapore: Association for Computing Machinery, 2017, pp. 269–271. DOI: 10.1145/3059454.3078710.

[41] Xuan Cao et al. "Fully screen-printed, large-area, and flexible active-matrix electrochromic displays using carbon nanotube thin-film transistors". In: *ACS nano* 10.11 (2016), pp. 9816–9822.

[42] Tom Carter et al. "UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces". In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. St. Andrews, Scotland, United Kingdom: Association for Computing Machinery, 2013, pp. 505–514. DOI: 10.1145/2501988.2502018.

[43] chemicum. *Supercapacitor - how to make, for a greener future*. YouTube. 2021. URL: https://www.youtube.com/watch?v=iQ3njhSnOA0.

[44] Tungpo Chen et al. "Conductive poly(3,4-ethylenedioxythiophene) is effectively degradable by hydrogen peroxide with iron (II) chloride". In: *Materials Chemistry and Physics* 242 (2020), p. 122509. DOI: https://doi.org/10.1016/j.matchemphys.2019.122509.

[45] Huanyu Cheng et al. "Analysis of a concentric coplanar capacitor for epidermal hydration sensing". In: *Sensors and Actuators A: Physical* 203 (2013), pp. 149–153.

[46] Yoram Chisik et al. "Through the Zoom Glass: Drawing Design Inspiration from Mediated Playful Interactions with Food and Child Personas". In: *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play*. CHI PLAY '21. Virtual Event, Austria: Association for Computing Machinery, 2021, pp. 294–300. DOI: 10.1145/3450337.3483452.

[47] Seokheun Choi. "Electrogenic Bacteria Promise New Opportunities for Powering, Sensing, and Synthesizing". In: *Small* 18.18 (2022), p. 2107902. DOI: https://doi.org/10.1002/smll.202107902.

[48] Sharon Lynn Chu et al. "'I Make, Therefore I Am': The Effects of Curriculum-Aligned Making on Children's Self-Identity". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 109–120. DOI: 10.1145/3025453.3025458.

[49] Yieu Chyan et al. "Laser-Induced Graphene by Multiple Lasing: Toward Electronics on Cloth, Paper, and Food". In: *ACS Nano* 12.3 (2018). PMID: 29436816, pp. 2176–2183. DOI: 10.1021/acsnano.7b08539.

[50] Adrian K. Clear et al. "Bearing an Open "Pandora's Box": HCI for Reconciling Everyday Food and Sustainability". In: *ACM Trans. Comput.-Hum. Interact.* 23.5 (Oct. 2016). DOI: 10.1145/2970817.

[51] Marcelo Coelho et al. "Pulp-Based Computing: A Framework for Building Computers out of Paper". In: *CHI '09 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '09. Boston, MA, USA: Association for Computing Machinery, 2009, pp. 3527–3528. DOI: 10.1145/1520340.1520525.

[52] Giulia Corniani and Hannes P. Saal. "Tactile innervation densities across the whole body". In: *Journal of Neurophysiology* 124.4 (2020). PMID: 32965159, pp. 1229–1240. DOI: 10.1152/jn.00313.2020.

[53] Marina F. Cosate de Andrade et al. "Life Cycle Assessment of Poly(Lactic Acid) (PLA): Comparison Between Chemical Recycling, Mechanical Recycling and Composting". en. In: *Journal of Polymers and the Environment* 24.4 (Dec. 2016), pp. 372–384. DOI: 10.1007/s10924-016-0787-2.

[54] Andrea Cuadra, David Goedicke, and J.D. Zamfirescu-Pereira. "Democratizing Design and Fabrication Using Speech: Exploring co-design with a voice assistant". In: *Proceedings of the 3rd Conference on Conversational User Interfaces*. CUI '21. Bilbao (online), Spain: Association for Computing Machinery, 2021. DOI: 10.1145/3469595.3469624.

[55] Haitao Cui et al. "A novel near-infrared light responsive 4D printed nanoarchitecture with dynamically and remotely controllable transformation". en. In: *Nano Research* 12.6 (June 2019), pp. 1381–1388. DOI: 10.1007/s12274-019-2340-9.

[56] Anthony A. D'Amico, Analise Debaie, and Amy M. Peterson. "Effect of layer thickness on irreversible thermal expansion and interlayer strength in fused deposition modeling". en. In: *Rapid Prototyping Journal* 23.5 (Aug. 2017), pp. 943–953. DOI: 10.1108/RPJ-05-2016-0077.

[57] Emily C. Davidson et al. "3D Printable and Reconfigurable Liquid Crystal Elastomers with Light-Induced Shape Memory via Dynamic Bond Exchange". en. In: *Advanced Materials* 32.1 (Jan. 2020), p. 1905682. DOI: 10.1002/adma.201905682.

[58] Hilary Davis et al. "Fantastic(e)Ating Food Futures: Reimagining Human Food Interaction". In: *Companion Publication of the 2020 ACM Designing Interactive Systems Conference*. DIS' 20 Companion. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 377–380. DOI: 10.1145/3393914.3395906.

[59] N. Delaporte et al. "Toward Low-Cost All-Organic and Biodegradable Li-Ion Batteries". en. In: *Nature Scientific Reports* 10.1 (Dec. 2020), p. 3812. DOI: 10.1038/s41598-020-60633-y.

[60] Maison G. DeNavarre. "Oils and fats, the historical cosmetics". In: *Journal of the American Oil Chemists' Society* 55.4 (Apr. 1978), pp. 435–437. DOI: 10.1007/BF02911908.

[61] Jialin Deng et al. "Logic Bonbon: Exploring Food as Computational Artifact". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3501926.

[62] Jialin Deng et al. "Mapping FoodHCI Futures". In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491101.3516401.

[63] Jialin Deng et al. "The Future of Human-Food Interaction". In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI EA '21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411763.3441312.

[64] Laura Devendorf and Daniela K. Rosner. "Reimagining Digital Fabrication as Performance Art". en. In: *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '15*. Seoul, Republic of Korea: ACM Press, 2015, pp. 555–566. DOI: 10.1145/2702613.2732507.

[65] Laura Devendorf et al. ""I Don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 6028–6039. DOI: 10.1145/2858036.2858192.

[66] Kristin N. Dew, Samantha Shorey, and Daniela Rosner. "Making within limits: towards salvage fabrication". en. In: *Proceedings of the 2018 Workshop on Computing within Limits - LIMITS '18*. Toronto, Ontario, Canada: ACM Press, 2018, pp. 1–11. DOI: 10.1145/3232617.3232626.

[67] Christine Dierk, Tomás Vega Gálvez, and Eric Paulos. "AlterNail: Ambient, Batteryless, Stateful, Dynamic Displays at your Fingertips". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 6754–6759. DOI: 10.1145/3025453.3025924.

[68] Christine Dierk, Molly Jane Pearce Nicholas, and Eric Paulos. "AlterWear: Battery-Free Wearable Displays for Opportunistic Interactions". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–11. DOI: 10.1145/3173574.3173794.

[69] Christine Dierk, Molly Jane Pearce Nicholas, and Eric Paulos. "AlterWear: Battery-Free Wearable Displays for Opportunistic Interactions". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 220:1–220:11. DOI: 10.1145/3173574.3173794.

[70] Christine Dierk, Tomás Vega Gálvez, and Eric Paulos. "AlterNail: Ambient, Batteryless, Stateful, Dynamic Displays at Your Fingertips". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 6754–6759. DOI: 10.1145/3025453.3025924.

[71] Christine Dierk et al. "HäirIÖ: Human Hair As Interactive Material". In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '18. Stockholm, Sweden: ACM, 2018, pp. 148–157. DOI: 10.1145/3173225.3173232.

[72] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. “Mapping the landscape of sustainable HCI”. en. In: *Proceedings of the 28th international conference on Human factors in computing systems - CHI ’10*. Atlanta, Georgia, USA: ACM Press, 2010, p. 1975. DOI: 10.1145/1753326.1753625.

[73] Markéta Dolejšová et al. “Crafting and Tasting Issues in Everyday Human-Food Interactions”. In: *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion*. DIS ’19 Companion. San Diego, CA, USA: Association for Computing Machinery, 2019, pp. 361–364. DOI: 10.1145/3301019.3319994.

[74] Markéta Dolejšová et al. “Designing Recipes for Digital Food Futures”. In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–8. DOI: 10.1145/3170427.3170622.

[75] Markéta Dolejšová et al. “Disrupting (More-than-) Human-Food Interaction: Experimental Design, Tangibles and Food-Tech Futures”. In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. DIS ’20. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 993–1004. DOI: 10.1145/3357236.3395437.

[76] Elzelinde van Doleweerd, Ferran Altarriba Bertran, and Miguel Bruns. “Incorporating Shape-Changing Food Materials Into Everyday Culinary Practices: Guidelines Informed by Participatory Sessions with Chefs Involving Edible PH-Responsive Origami Structures”. In: *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’22. Daejeon, Republic of Korea: Association for Computing Machinery, 2022. DOI: 10.1145/3490149.3501315.

[77] Boris Dyatkin et al. “Development of a Green Supercapacitor Composed Entirely of Environmentally Friendly Materials”. In: *ChemSusChem* 6.12 (2013), pp. 2269–2280. DOI: https://doi.org/10.1002/cssc.201300852.

[78] David Eickhoff, Stefanie Mueller, and Patrick Baudisch. “Destructive Games: Creating Value by Destroying Valuable Physical Objects”. en. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI ’16*. Santa Clara, California, USA: ACM Press, 2016, pp. 3970–3974. DOI: 10.1145/2858036.2858113.

[79] Abdallah El Ali et al. “ThermalWear: Exploring Wearable On-chest Thermal Displays to Augment Voice Messages with Affect”. en. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, Apr. 2020, pp. 1–14. DOI: 10.1145/3313831.3376682.

[80] I.A. Shehata Elhelf et al. “High intensity focused ultrasound: The fundamentals, clinical applications and research trends”. In: *Diagnostic and Interventional Imaging* 99.6 (2018), pp. 349–359. DOI: https://doi.org/10.1016/j.diii.2018.03.001.

[81] Nejla B. Erdal and Minna Hakkarainen. “Degradation of Cellulose Derivatives in Laboratory, Man-Made, and Natural Environments”. In: *Biomacromolecules* 23.7 (2022). PMID: 35763720, pp. 2713–2729. DOI: 10.1021/acs.biomac.2c00336.

[82] Shah Fahad et al. “Recent progress in the synthesis of silver nanowires and their role as conducting materials”. en. In: *Journal of Materials Science* 54.2 (Jan. 2019), pp. 997–1035. DOI: 10.1007/s10853-018-2994-9.

[83] Aaron Fenster, Dónal B Downey, and H Neale Cardinal. “Three-dimensional ultrasound imaging”. In: *Physics in Medicine & Biology* 46.5 (May 2001), R67. DOI: 10.1088/0031-9155/46/5/201.

[84] Piyum Fernando, Matthew Pandelakis, and Stacey Kuznetsov. “Practicing DIYBiology In An HCI Setting”. In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 2064–2071. DOI: 10.1145/2851581.2892325.

[85] David J. Finn, Mustafa Lotya, and Jonathan N. Coleman. “Inkjet Printing of Silver Nanowire Networks”. In: *ACS Applied Materials & Interfaces* 7.17 (2015). PMID: 25874531, pp. 9254–9261. DOI: 10.1021/acsami.5b01875.

[86] Euan Freeman et al. “Point-and-Shake: Selecting from Levitating Object Displays”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–10. DOI: 10.1145/3173574.3173592.

[87] Bettina Friedel et al. “Effects of Layer Thickness and Annealing of PEDOT:PSS Layers in Organic Photodetectors”. In: *Macromolecules* 42.17 (2009), pp. 6741–6747. DOI: 10.1021/ma901182u.

[88] Bruce Fulford. *The Composting Greenhouse at New Alchemy Institute: A Report on Two Years of Operation and Monitoring*. Tech. rep. New Alchemy Institute Research Report No.3. BiioThermal Associates, 1986.

[89] Takuro Furumoto et al. “Midair Balloon Interface: A Soft and Lightweight Midair Object for Proximate Interactions”. In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 783–795. DOI: 10.1145/3472749.3474786.

[90] Yulia Galagan et al. “ITO-free flexible organic solar cells with printed current collecting grids”. In: *Solar Energy Materials and Solar Cells* 95.5 (2011), pp. 1339–1343.

[91] William Gaver et al. “My Naturewatch Camera: Disseminating Practice Research with a Cheap and Easy DIY Design”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI ’19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300532.

[92] Tom Gayler. “Towards Edible Interfaces: Designing Interactions with Food”. In: *Proceedings of the 19th ACM International Conference on Multimodal Interaction*. ICMI ’17. Glasgow, UK: Association for Computing Machinery, 2017, pp. 623–627. DOI: 10.1145/3136755.3137030.

[93] Tom Gayler, Corina Sas, and Vaiva Kalnikaite. "Material Food Probe: Personalized 3D Printed Flavors for Emotional Communication in Intimate Relationships". In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. DIS '20. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 965–978. DOI: 10.1145/3357236.3395533.

[94] Tom Gayler, Corina Sas, and Vaiva Kalnikaite. "Taste Your Emotions: An Exploration of the Relationship between Taste and Emotional Experience for HCI". In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS '19. San Diego, CA, USA: Association for Computing Machinery, 2019, pp. 1279–1291. DOI: 10.1145/3322276.3322336.

[95] Elisa Giaccardi et al. "Growing traces on objects of daily use: a product design perspective for HCI". en. In: *Proceedings of the 2014 conference on Designing interactive systems - DIS '14*. Vancouver, BC, Canada: ACM Press, 2014, pp. 473–482. DOI: 10.1145/2598510.2602964.

[96] Hyunjae Gil et al. "Whiskers: Exploring the Use of Ultrasonic Haptic Cues on the Face". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. DOI: 10.1145/3173574.3174232.

[97] Alex Golberg, Haim D. Rabinowitch, and Boris Rubinsky. "Zn/Cu-vegetative batteries, bioelectrical characterizations, and primary cost analyses". In: *Journal of Renewable and Sustainable Energy* 2.3 (2010), p. 033103. DOI: 10.1063/1.3427222.

[98] Nora Goldstein, Paula Luu, and Stephanie Motta. *BioCycle Nationwide Survey: Residential Food Waste Collection Access In The U.S*. URL: https://www.biocycle.net/residential-food-waste-collection-access-in-u-s/.

[99] Gozde Goncu-Berk. "Smart Textiles and Clothing: An Opportunity or A Threat for Sustainability". In: *Proceedings of the Textile Intersections*. London, UK: Loughborough University, 2019.

[100] Bona Goo, Chae-Hui Hong, and Keun Park. "4D printing using anisotropic thermal deformation of 3D-printed thermoplastic parts". en. In: *Materials & Design* 188 (Mar. 2020), p. 108485. DOI: 10.1016/j.matdes.2020.108485.

[101] Daniel Gooch and Leon Watts. "Communicating Social Presence Through Thermal Hugs". en. In: *Ubicomp Proceedings of First Workshop on Social Interaction in Spatially Separated Environments (SISSI '10)*. Copenhagen, Denmark: ACM, 2010, p. 11.

[102] Daniel Gooch and Leon Watts. "It's neat to feel the heat: how can we hold hands at a distance?" en. In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. Austin Texas USA: ACM, May 2012, pp. 1535–1540. DOI: 10.1145/2212776.2223668.

[103] Karthik Gopalan et al. "Quantitative anatomy mimicking slice phantoms". In: *Magnetic Resonance in Medicine* 86.2 (2021), pp. 1159–1166. DOI: `https://doi.org/10.1002/mrm.28740`.

[104] Phillip Gough et al. "Design, Mould, Grow!: A Fabrication Pipeline for Growing 3D Designs Using Myco-Materials". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. DOI: `10.1145/3544548.3580958`.

[105] Eduard Georges Groutars et al. "Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: `10.1145/3491102.3517713`.

[106] Jianzhe Gu et al. "Geodesy: Self-rising 2.5D Tiles by Printing along 2D Geodesic Closed Path". en. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. Glasgow, Scotland Uk: ACM Press, 2019, pp. 1–10. DOI: `10.1145/3290605.3300267`.

[107] Patrick Haggard and Lieke de Boer. "Oral somatosensory awareness". In: *Neuroscience & Biobehavioral Reviews* 47 (2014), pp. 469–484. DOI: `https://doi.org/10.1016/j.neubiorev.2014.09.015`.

[108] Charles Alan Hamilton, Gursel Alici, and Marc in het Panhuis. "3D printing Vegemite and Marmite: Redefining "breadboards"". In: *Journal of Food Engineering* 220 (2018). 3D Printed Food – Design and Technology, pp. 83–88. DOI: `https://doi.org/10.1016/j.jfoodeng.2017.01.008`.

[109] Mallory L Hammock et al. "25th anniversary article: the evolution of electronic skin (e-skin): a brief history, design considerations, and recent progress". In: *Advanced materials* 25.42 (2013), pp. 5997–6038.

[110] Arnbjörn O. Hanstveit. "Biodegradability of petroleum waxes and beeswax in an adapted CO2 evolution test". In: *Chemosphere* 25.4 (1992), pp. 605–620. DOI: `https://doi.org/10.1016/0045-6535(92)90291-X`.

[111] Ollie Hanton et al. "FabricatINK: Personal Fabrication of Bespoke Displays Using Electronic Ink from Upcycled E Readers". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: `10.1145/3491102.3501844`.

[112] Marvin Harris. *Good to eat : riddles of food and culture / Marvin Harris*. English. New York, NY: Simon and Schuster New York, 1985, 289 p.

[113] Chris Harrison and Haakon Faste. "Implications of Location and Touch for On-Body Projected Interfaces". In: *Proceedings of the 2014 Conference on Designing Interactive Systems*. DIS '14. Vancouver, BC, Canada: Association for Computing Machinery, 2014, pp. 543–552. DOI: `10.1145/2598510.2598587`.

[114] Lauren Hayes and Jessica Rajko. "Towards an Aesthetics of Touch". In: *Proceedings of the 4th International Conference on Movement Computing*. MOCO '17. London, United Kingdom: Association for Computing Machinery, 2017. DOI: 10.1145/3077981.3078028.

[115] K. L. Hooker and G. R. Marzolf. "Differential Decomposition of Leaves in Grassland and Gallery Forest Reaches of Kings Creek". In: *Transactions of the Kansas Academy of Science (1903-)* 90.1/2 (1987), pp. 17–24.

[116] Kasper Hornbæk et al. "What Do We Mean by "Interaction"? An Analysis of 35 Years of CHI". In: *ACM Trans. Comput.-Hum. Interact.* 26.4 (July 2019). DOI: 10.1145/3325285.

[117] Peter J Houghton. "The scientific basis for the reputed activity of Valerian". In: *Journal of Pharmacy and Pharmacology* 51.5 (1999), pp. 505–512.

[118] Noura Howell et al. "Biosignals As Social Cues: Ambiguity and Emotional Interpretation in Social Displays of Skin Conductance". In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS '16. Brisbane, QLD, Australia: ACM, 2016, pp. 865–870. DOI: 10.1145/2901790.2901850.

[119] Helen H. Hsu et al. "An Eco-Friendly, Nanocellulose/RGO/in Situ Formed Polyaniline for Flexible and Free-Standing Supercapacitors". In: *ACS Sustainable Chemistry & Engineering* 7.5 (2019), pp. 4766–4776. DOI: 10.1021/acssuschemeng.8b04947.

[120] Liangbing Hu et al. "Highly conductive paper for energy-storage devices". In: *Proceedings of the National Academy of Sciences* 106.51 (2009), pp. 21490–21494. DOI: 10.1073/pnas.0908858106.

[121] Kunpeng Huang et al. "WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field". In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1143–1158. DOI: 10.1145/3461778.3462105.

[122] Xian Huang et al. "Epidermal differential impedance sensor for conformal skin hydration monitoring". In: *Biointerphases* 7.1 (2012), p. 52.

[123] Xian Huang et al. "Materials and designs for wireless epidermal sensors of hydration and strain". In: *Advanced Functional Materials* 24.25 (2014), pp. 3846–3854.

[124] Amy Hurst and Jasmine Tobias. "Empowering Individuals with Do-It-Yourself Assistive Technology". In: *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '11. Dundee, Scotland, UK: Association for Computing Machinery, 2011, pp. 11–18. DOI: 10.1145/2049536.2049541.

[125] Miwa Ikemiya and Daniela K. Rosner. "Broken probes: toward the design of worn media". en. In: *Personal and Ubiquitous Computing* 18.3 (Mar. 2014), pp. 671–683. DOI: 10.1007/s00779-013-0690-y.

[126] Transforma Insights. *Current IoT Forecast Highlights*. Transforma Insights. 2024. URL: https://www.marketsandmarkets.com/Market-Reports/internet-of-things-market-573.html.

[127] Jorge Iranzo Bartolomé et al. "Thermal Interaction for Improving Tactile Artwork Depth and Color-Depth Appreciation for Visually Impaired People". en. In: *Electronics* 9.11 (Nov. 2020), p. 1939. DOI: 10.3390/electronics9111939.

[128] Yasha Iravantchi, Mayank Goel, and Chris Harrison. "BeamBand: Hand Gesture Sensing with Ultrasonic Beamforming". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–10. DOI: 10.1145/3290605.3300245.

[129] Yasha Iravantchi, Mayank Goel, and Chris Harrison. "Digital Ventriloquism: Giving Voice to Everyday Objects". In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–10. DOI: 10.1145/3313831.3376503.

[130] Yasha Iravantchi et al. "Interferi: Gesture Sensing Using On-Body Acoustic Interferometry". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300506.

[131] Ayaka Ishii and Itiro Siio. "BubBowl: Display Vessel Using Electrolysis Bubbles in Drinkable Beverages". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST '19. New Orleans, LA, USA: Association for Computing Machinery, 2019, pp. 619–623. DOI: 10.1145/3332165.3347923.

[132] Ayaka Ishii et al. "Fabricating Wooden Circuit Boards by Laser Beam Machining". In: *The Adjunct Publication of the 34th Annual ACM Symposium on User Interface Software and Technology*. New York, NY, USA: Association for Computing Machinery, 2021, pp. 109–111.

[133] Mitch Jacoby. *It's time to get serious about recycling lithium-ion batteries*. July 2019.

[134] Harshika Jain, Kexin Lu, and Lining Yao. "Hydrogel-Based DIY Underwater Morphing Artifacts: A Morphing and Fabrication Technique to Democratize the Creation of Controllable Morphing 3D Underwater Structures with Low-Cost, Easily Available Hydrogel Beads Adhered to a Substrate." In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1242–1252. DOI: 10.1145/3461778.3462136.

[135] Walther Jensen et al. "TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays". In: *Advances in Human-Computer Interaction* 2019 (May 2019), pp. 1–14. DOI: 10.1155/2019/1340182.

[136] Jungho Jin et al. "Chitin Nanofiber Transparent Paper for Flexible Green Electronics". In: *Advanced Materials* 28.26 (2016), pp. 5169–5175. DOI: https://doi.org/10.1002/adma.201600336.

[137] Arata Jingu et al. "LipNotif: Use of Lips as a Non-Contact Tactile Notification Interface Based on Ultrasonic Tactile Presentation". In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 13–23. DOI: 10.1145/3472749.3474732.

[138] Philip N. Johnson-Laird. *Mental models : towards a cognitive science of language, inference, and consciousness*. Excerpts available on Google Books. Cambridge, MA, USA: Harvard University Press, 1983, p. 528.

[139] Martin Jonsson et al. "The Aesthetics of Heat: Guiding Awareness with Thermal Stimuli". en. In: *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. Eindhoven Netherlands: ACM, Feb. 2016, pp. 109–117. DOI: 10.1145/2839462.2839487.

[140] Annemarie Joyce. *Thermal Processing of Food 101: An introduction to Pasteurization*. Safefood 360. 2020. URL: https://safefood360.com/2020/10/thermal-processing-of-food-101-pasteurization-introduction/ (visited on 10/22/2020).

[141] Jincy Parayangattil Jyothibasu and Rong-Ho Lee. "Facile, Scalable, Eco-Friendly Fabrication of High-Performance Flexible All-Solid-State Supercapacitors". In: *Polymers* 10.11 (2018). DOI: 10.3390/polym10111247.

[142] Hiroki Kaimoto et al. "ExpandFab: Fabricating Objects Expanding and Changing Shape with Heat". en. In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. Sydney NSW Australia: ACM, Feb. 2020, pp. 153–164. DOI: 10.1145/3374920.3374949.

[143] Cindy Hsin-Liu Kao et al. "EarthTones: Chemical Sensing Powders to Detect and Display Environmental Hazards through Color Variation". In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 872–883. DOI: 10.1145/3027063.3052754.

[144] Hsin-Liu (Cindy) Kao. "Hybrid Body Craft". In: *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems*. DIS '17 Companion. Edinburgh, United Kingdom: ACM, 2017, pp. 391–392. DOI: 10.1145/3064857.3079167.

[145] Hsin-Liu (Cindy) Kao et al. "ChromoSkin: Towards Interactive Cosmetics Using Thermochromic Pigments". In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 3703–3706. DOI: 10.1145/2851581.2890270.

[146] Hsin-Liu (Cindy) Kao et al. "DuoSkin: Rapidly Prototyping On-skin User Interfaces Using Skin-friendly Materials". In: *Proceedings of the 2016 ACM International Symposium on Wearable Computers*. ISWC '16. Heidelberg, Germany: ACM, 2016, pp. 16–23. DOI: 10.1145/2971763.2971777.

[147] Hsin-Liu (Cindy) Kao et al. "DuoSkin: Rapidly Prototyping on-Skin User Interfaces Using Skin-Friendly Materials". In: *Proceedings of the 2016 ACM International Symposium on Wearable Computers*. ISWC '16. Heidelberg, Germany: Association for Computing Machinery, 2016, pp. 16–23. DOI: 10.1145/2971763.2971777.

[148] Hsin-Liu (Cindy) Kao et al. "Skinmorph: Texture-Tunable on-Skin Interface through Thin, Programmable Gel". In: *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ISWC '18. Singapore, Singapore: Association for Computing Machinery, 2018, pp. 196–203. DOI: 10.1145/3267242.3267262.

[149] Hsin-Liu (Cindy) Kao et al. "Skinmorph: Texture-Tunable on-Skin Interface through Thin, Programmable Gel". In: *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ISWC '18. Singapore, Singapore: Association for Computing Machinery, 2018, pp. 196–203. DOI: 10.1145/3267242.3267262.

[150] Mahya Karami-Mosammam et al. "Stretchable and Biodegradable Batteries with High Energy and Power Density". In: *Advanced Materials* 34.32 (2022), p. 2204457. DOI: https://doi.org/10.1002/adma.202204457.

[151] Elvin Karana, Bahareh Barati, and Elisa Giaccardi. "Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts." In: *International Journal of Design* 14.3 (2020).

[152] Elvin Karana et al. "When the Material Grows: A Case Study on Designing (with) Mycelium-based Materials". en. In: *International Journal of Design* 12.2 (2018), p. 18.

[153] Hiroki Kawahara, Kaito Yamao, and Kentaro Oda. "Magic Drops:Food 3D Printing of Colored Liquid Balls by Ultrasound Levitation". In: *Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. UIST '22 Adjunct. Bend, OR, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3526114.3561348.

[154] Yoshihiro Kawahara et al. "Instant Inkjet Circuits: Lab-Based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices". In: *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. UbiComp '13. Zurich, Switzerland: Association for Computing Machinery, 2013, pp. 363–372. DOI: 10.1145/2493432.2493486.

[155] John Keeling. "Graphite: properties, uses and South Australian resources". en. In: *MESA Journal* 84 (3 2017), pp. 21–44.

[156] J E Kennedy, G R ter Haar, and D Cranston. "High intensity focused ultrasound: surgery of the future?" In: *The British Journal of Radiology* 76.909 (2003). PMID: 14500272, pp. 590–599. DOI: 10.1259/bjr/17150274.

[157] Arshad Khan et al. "Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits Using a Commodity Inkjet Printer". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST '19. New Orleans, LA, USA: Association for Computing Machinery, 2019, pp. 341–354. DOI: 10.1145/3332165.3347892.

[158] Rohit Ashok Khot et al. "EdiPulse: Investigating a Playful Approach to Self-Monitoring through 3D Printed Chocolate Treats". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 6593–6607. DOI: 10.1145/3025453.3025980.

[159] Rohit Ashok Khot et al. "TastyBeats: Designing Palatable Representations of Physical Activity". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 2933–2942. DOI: 10.1145/2702123.2702197.

[160] Dae-Hyeong Kim et al. "Epidermal electronics". In: *science* 333.6044 (2011), pp. 838–843.

[161] Jayoung Kim et al. "A wearable fingernail chemical sensing platform: pH sensing at your fingertips". In: *Talanta* 150 (2016), pp. 622–628. DOI: https://doi.org/10.1016/j.talanta.2015.12.083.

[162] Sunyoung Kim and Eric Paulos. "Practices in the creative reuse of e-waste". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 2395–2404. DOI: 10.1145/1978942.1979292.

[163] Yong Hyun Kim et al. "Achieving high efficiency and improved stability in ITO-free transparent organic light-emitting diodes with conductive polymer electrodes". In: *Advanced Functional Materials* 23.30 (2013), pp. 3763–3769.

[164] You-Soo Kim et al. "Regional thickness of facial skin and superficial fat: Application to the minimally invasive procedures". In: *Clinical Anatomy* 32.8 (2019), pp. 1008–1018. DOI: https://doi.org/10.1002/ca.23331.

[165] Eric Klarenbeek. *The Mycelium Project - Print and Grow*. https://ericklarenbeek.com. 2011.

[166] Michael Klements. *Making An Ultra Low Power Arduino Pro*. 2021.

[167] B. Kneafsey, M. O'Shaughnessy, and K.C. Condon. "The use of calcium alginate dressings in deep hand burns". In: *Burns* 22.1 (1996), pp. 40–43. DOI: https://doi.org/10.1016/0305-4179(95)00066-6.

[168] Cindy Kohtala. "Making "Making" Critical: How Sustainability is Constituted in Fab Lab Ideology". en. In: *The Design Journal* 20.3 (May 2017), pp. 375–394. DOI: 10.1080/14606925.2016.1261504.

[169] Anastasia Koivikko et al. "Biodegradable, Flexible and Transparent Tactile Pressure Sensor Based on Rubber Leaf Skeletons". en. In: *IEEE Sensors Journal* Early Access (2021), pp. 1–1. DOI: 10.1109/JSEN.2021.3078807.

[170] Michinari Kono et al. "Pre-Eating Play: Fabrication Experiences for Playful Human-Food Interaction". In: *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*. CHI PLAY '20. Virtual Event, Canada: Association for Computing Machinery, 2020, pp. 160–168. DOI: 10.1145/3410404.3414228.

[171] Leonard Koren. *Wabi-sabi for artists, designers, poets & philosophers*. Point Reyes, CA, USA: Imperfect Publishing, 2008.

[172] Katrina Krämer. *Biodegradable batteries could be made from modified proteins*. Chemistry World. 2019. URL: https://www.chemistryworld.com/news/biodegradable-batteries-could-be-made-from-modified-proteins/3010902.article (visited on 08/29/2019).

[173] Siddharth Krishnan et al. "Multimodal epidermal devices for hydration monitoring". In: *Microsystems & nanoengineering* 3.1 (2017), pp. 1–11.

[174] Ruediger Kuehr, David Hirsch, and Terry Collins. *Global E-Waste Monitor 2024*. United Nations Institute for Training and Research. 2024. URL: https://globalewaste.org/ (visited on 06/27/2024).

[175] Stacey Kuznetsov and Eric Paulos. "Rise of the Expert Amateur: DIY Projects, Communities, and Cultures". In: *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*. NordiCHI '10. Reykjavik, Iceland: Association for Computing Machinery, 2010, pp. 295–304. DOI: 10.1145/1868914.1868950.

[176] Stacey Kuznetsov et al. "Screenprinting and TEI: Supporting Engagement with STEAM through DIY Fabrication of Smart Materials". In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '18. Stockholm, Sweden: Association for Computing Machinery, 2018, pp. 211–220. DOI: 10.1145/3173225.3173253.

[177] Hyosun Kwon et al. "FugaciousFilm: Exploring Attentive Interaction with Ephemeral Material". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 1285–1294. DOI: 10.1145/2702123.2702206.

[178] lasersaber. *Easy DIY Graphene SuperCapacitors*. YouTube. 2015. URL: https://www.youtube.com/watch?v=Ar3C5JgzhgE.

[179] Bruno Latour. "On Technical Mediation". In: *Common Knowledge* 3.2 (1994), pp. 29–64.

[180] Jenni Lauwrens. "Touch as an aesthetic experience". In: *Journal of Visual Art Practice* 18.4 (2019), pp. 323–341. DOI: 10.1080/14702029.2019.1680510.

[181] Amanda Lazar et al. "Why We Use and Abandon Smart Devices". In: *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. UbiComp '15. Osaka, Japan: Association for Computing Machinery, 2015, pp. 635–646. DOI: 10.1145/2750858.2804288.

[182] Eldy S. Lazaro Vasquez, Hao-Chuan Wang, and Katia Vega. "Introducing the Sustainable Prototyping Life Cycle for Digital Fabrication to Designers". en. In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. Eindhoven Netherlands: ACM, July 2020, pp. 1301–1312. DOI: 10.1145/3357236.3395510.

[183] Inhwa Lee et al. "Simultaneously Enhancing the Cohesion and Electrical Conductivity of PEDOT:PSS Conductive Polymer Films using DMSO Additives". In: *ACS Applied Materials & Interfaces* 8.1 (2016). PMID: 26642259, pp. 302–310. DOI: 10.1021/acsami.5b08753.

[184] Sunmin Lee and Thecla Schiphorst. "Warmth and Affection: Exploring Thermal Sensation in the Design of Parent-Child Distant Interaction". en. In: *Human-Computer Interaction. Novel User Experiences*. Ed. by Masaaki Kurosu. Vol. 9733. Series Title: Lecture Notes in Computer Science. Cham: Springer International Publishing, 2016, pp. 3–14. DOI: 10.1007/978-3-319-39513-5_1.

[185] Wonjun Lee and Youn-kyung Lim. "Explorative research on the heat as an expression medium: focused on interpersonal communication". en. In: *Personal and Ubiquitous Computing* 16.8 (Dec. 2012), pp. 1039–1049. DOI: 10.1007/s00779-011-0424-y.

[186] Ting Lei et al. "Biocompatible and totally disintegrable semiconducting polymer for ultrathin and ultralightweight transient electronics". In: *Proceedings of the National Academy of Sciences* 114.20 (2017), pp. 5107–5112. DOI: 10.1073/pnas.1701478114.

[187] Steven K. Leist and Jack Zhou. "Current status of 4D printing technology and the potential of light-reactive smart materials as 4D printable materials". en. In: *Virtual and Physical Prototyping* 11.4 (Oct. 2016), pp. 249–262. DOI: 10.1080/17452759.2016.1198630.

[188] Steven K. Leist et al. "Investigating the shape memory properties of 4D printed polylactic acid (PLA) and the concept of 4D printing onto nylon fabrics for the creation of smart textiles". en. In: *Virtual and Physical Prototyping* 12.4 (Oct. 2017), pp. 290–300. DOI: 10.1080/17452759.2017.1341815.

[189] Rongfeng Li, Liu Wang, and Lan Yin. "Materials and Devices for Biodegradable and Soft Biomedical Electronics". In: *Materials* 11.11 (2018). DOI: 10.3390/ma11112108.

[190] Weiwei Li, Azat Meredov, and Atif Shamim. "Silver Nanowire based Flexible, Transparent, Wideband Antenna for 5G Band Application". In: *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*. Atlanta, GA, USA: IEEE, 2019, pp. 275–276. DOI: 10.1109/APUSNCURSINRSM.2019.8888371.

[191] Wenhui Li et al. “Biodegradable Materials and Green Processing for Green Electronics”. en. In: *Advanced Materials* 32.33 (Aug. 2020), p. 2001591. DOI: 10.1002/adma.202001591.

[192] Po-Chen Lin et al. “Fabricating efficient flexible organic photovoltaics using an eco-friendly cellulose nanofibers/silver nanowires conductive substrate”. In: *Chemical Engineering Journal* 405 (2021), p. 126996. DOI: https://doi.org/10.1016/j.cej.2020.126996.

[193] Richard Lin et al. “Beyond Schematic Capture: Meaningful Abstractions for Better Electronics Design Tools”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI ’19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300513.

[194] Shiying Lin, Feijun Wang, and Ziqiang Shao. “Biomass applied in supercapacitor energy storage devices”. In: *Journal of Materials Science* 56.3 (Jan. 2021), pp. 1943–1979. DOI: 10.1007/s10853-020-05356-1.

[195] Ying-Ju Lin et al. “FoodFab: Creating Food Perception Illusions Using Food 3D Printing”. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–13. DOI: 10.1145/3313831.3376421.

[196] Andrea Ling. “Design by Decay, Decay by Design”. en. MA thesis. MIT Media Lab, 2018, p. 139.

[197] Darren J Lipomi et al. “Electronic properties of transparent conductive films of PEDOT: PSS on stretchable substrates”. In: *Chemistry of Materials* 24.2 (2012), pp. 373–382.

[198] Lanlan Liu et al. “Green synthesis of silver nanowires via ultraviolet irradiation catalyzed by phosphomolybdic acid and their antibacterial properties”. en. In: *New Journal of Chemistry* 37.7 (2013), p. 2179. DOI: 10.1039/c3nj00135k.

[199] Lin Liu et al. “Spatial Engineering of Microbial Consortium for Long-Lasting, Self-Sustaining, and High-Power Generation in a Bacteria-Powered Biobattery”. In: *Advanced Energy Materials* 11.22 (2021), p. 2100713. DOI: https://doi.org/10.1002/aenm.202100713.

[200] Szu-Yu (Cyn) Liu. “To Decompose Is to Create: Supporting Creativity by Incorporating Nature in Design”. en. In: *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition*. Singapore Singapore: ACM, June 2017, pp. 484–489. DOI: 10.1145/3059454.3078696.

[201] Szu-Yu (Cyn) Liu, Jeffrey Bardzell, and Shaowen Bardzell. “Decomposition as Design: Co-Creating (with) Natureculture”. en. In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI ’19*. Tempe, Arizona, USA: ACM Press, 2019, pp. 605–614. DOI: 10.1145/3294109.3295653.

[202] Vincent Liu et al. “Ambient Backscatter: Wireless Communication out of Thin Air”. In: *SIGCOMM Comput. Commun. Rev.* 43.4 (Aug. 2013), pp. 39–50. DOI: 10.1145/2534169.2486015.

[203] Joanne Lo et al. “Aesthetic Electronics: Designing, Sketching, and Fabricating Circuits through Digital Exploration”. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST ’16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 665–676. DOI: 10.1145/2984511.2984579.

[204] Joanne Lo et al. “Skintillates: Designing and Creating Epidermal Interactions”. In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS ’16. Brisbane, QLD, Australia: Association for Computing Machinery, 2016, pp. 853–864. DOI: 10.1145/2901790.2901885.

[205] Joanne Lo et al. “Skintillates: Designing and Creating Epidermal Interactions”. In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS ’16. Brisbane, QLD, Australia: ACM, 2016, pp. 853–864. DOI: 10.1145/2901790.2901885.

[206] Markus Lochtefeld, Anna Dagmar Bille Milthers, and Timothy Merritt. “Staging Constructionist Learning about Energy for Children with Electrochromic Displays and Low-Cost Materials”. In: *20th International Conference on Mobile and Ubiquitous Multimedia*. MUM 2021. Leuven, Belgium: Association for Computing Machinery, 2021, pp. 73–83. DOI: 10.1145/3490632.3490654.

[207] Anders Lundström and Ylva Fernaeus. “Making Crank-Powered Interactions: Methods, Demonstrators, Materials”. In: *Designing Interactive Systems Conference*. DIS ’22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 913–924. DOI: 10.1145/3532106.3533453.

[208] Michal Luria et al. “Destruction, Catharsis, and Emotional Release in Human-Robot Interaction”. en. In: *ACM Transactions on Human-Robot Interaction* 9.4 (June 2020), pp. 1–19. DOI: 10.1145/3385007.

[209] Irene Maldini. “Attachment, Durability and the Environmental Impact of Digital DIY”. In: *The Design Journal* 19.1 (2016), pp. 141–157. DOI: 10.1080/14606925.2016.1085213.

[210] Ilan Mandel and Wendy Ju. “Recapturing Product as Material Supply: Hoverboards as Garbatrage”. In: *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS ’23. Pittsburgh, PA, USA: Association for Computing Machinery, 2023, pp. 564–579. DOI: 10.1145/3563657.3596128.

[211] Teunis van Manen, Shahram Janbaz, and Amir A. Zadpoor. “Programming 2D/3D shape-shifting with hobbyist 3D printers”. en. In: *Materials Horizons* 4.6 (2017), pp. 1064–1069. DOI: 10.1039/C7MH00269F.

[212] Libu Manjakkal et al. "Natural Jute Fibre-Based Supercapacitors and Sensors for Eco-Friendly Energy Autonomous Systems". In: *Advanced Sustainable Systems* 5.3 (2021), p. 2000286. DOI: https://doi.org/10.1002/adsu.202000286.

[213] Jennifer C. Mankoff et al. "Environmental sustainability and interaction". en. In: *CHI '07 extended abstracts on Human factors in computing systems - CHI '07*. San Jose, CA, USA: ACM Press, 2007, p. 2121. DOI: 10.1145/1240866.1240963.

[214] Alex Mariakakis et al. "EcoPatches: Maker-Friendly Chemical-Based UV Sensing". In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. DIS '20. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 1983–1994. DOI: 10.1145/3357236.3395424.

[215] MarketsandMarkets. *IoT Market by Component (Hardware, Software Solutinos and Services), Organization Size, Focus Area (Smart Manufacturing, Smart Energy and Utilities, and Smart Retail) and Region - Global Forecasts to 2026*. Marketsand-Markets. 2022. URL: https://www.marketsandmarkets.com/Market-Reports/internet-of-things-market-573.html.

[216] MarketsandMarkets. *Wireless Charging Market with COVID-19 Impact by Implementation (Transmitters, Receivers), Technology (Magnetic Resonance, Inductive, Radio Frequency), Application (Consumer Electronics, Healthcare, Automotive), and Region - Global Forecast to 2026*. MarketsandMarkets Research. 2021. URL: https://www.marketsandmarkets.com/Market-Reports/wireless-charging-market-640.html (visited on 01/01/2021).

[217] Eric Markvicka et al. "ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: ACM, 2019, 632:1–632:10. DOI: 10.1145/3290605.3300862.

[218] Joe Marshall et al. "Sensory Alignment in Immersive Entertainment". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. DOI: 10.1145/3290605.3300930.

[219] Claire Martin. "Anger Rooms: A Smashing New Way to Relieve Stress". In: *The New York Times* Section BU (Nov. 2016), p. 4.

[220] Asier Marzo. "GauntLev: A Wearable to Manipulate Free-Floating Objects". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 3277–3281. DOI: 10.1145/2858036.2858370.

[221] Atsushi Matsubayashi, Yasutoshi Makino, and Hiroyuki Shinoda. "Direct Finger Manipulation of 3D Object Image with Ultrasound Haptic Feedback". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–11. DOI: 10.1145/3290605.3300317.

[222] Timothy P McNamara. *Semantic priming: Perspectives from memory and word recognition*. London, England, UK: Psychology Press, 2005.

[223] Janis Lena Meissner et al. "Do-It-Yourself Empowerment as Experienced by Novice Makers with Disabilities". In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS '17. Edinburgh, United Kingdom: Association for Computing Machinery, 2017, pp. 1053–1065. DOI: 10.1145/3064663.3064674.

[224] David A. Mellis and Leah Buechley. "Do-It-Yourself Cellphones: An Investigation into the Possibilities and Limits of High-Tech Diy". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1723–1732. DOI: 10.1145/2556288.2557309.

[225] Gustav Metzger. *Damaged nature, auto-destructive art*. London, England: Coracle Press, 1996.

[226] Jussi Mikkonen et al. "OJAS: Open Source Bi-Directional Inductive Power Link". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1049–1058. DOI: 10.1145/2556288.2557041.

[227] Douglas L. Miller et al. "Overview of Therapeutic Ultrasound Applications and Safety Considerations". In: *Journal of Ultrasound in Medicine* 31.4 (2012), pp. 623–634. DOI: https://doi.org/10.7863/jum.2012.31.4.623.

[228] Milica Milošević et al. "Biodegradation of cotton and cotton/polyester fabrics impregnated with Ag/TiO2 nanoparticles in soil". In: *Carbohydrate Polymers* 158 (2017), pp. 77–84. DOI: https://doi.org/10.1016/j.carbpol.2016.12.006.

[229] Rachel M. Miriani, Mohammad Reza Abidian, and Daryl R. Kipke. "Cytotoxic analysis of the conducting polymer PEDOT using myocytes". In: *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. Vancouver, BC, Canada: IEEE, 2008, pp. 1841–1844. DOI: 10.1109/IEMBS.2008.4649538.

[230] Samir S. Mitragotri. "Healing sound: the use of ultrasound in drug delivery and other therapeutic applications". In: *Nature Reviews Drug Discovery* 4 (2005), pp. 255–260.

[231] Homei Miyashita. "Norimaki Synthesizer: Taste Display Using Ion Electrophoresis in Five Gels". In: *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI EA '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–6. DOI: 10.1145/3334480.3382984.

[232] Homei Miyashita. "Taste Display That Reproduces Tastes Measured by a Taste Sensor". In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. UIST '20. Virtual Event, USA: Association for Computing Machinery, 2020, pp. 1085–1093. DOI: 10.1145/3379337.3415852.

[233] Mako Miyatake et al. "Flower Jelly Printer: Slit Injection Printing for Parametrically Designed Flower Jelly". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411764.3445346.

[234] Moran Mizrahi et al. "Digital Gastronomy: Methods & Recipes for Hybrid Cooking". In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 541–552. DOI: 10.1145/2984511.2984528.

[235] Massimo Montanari. *Food is Culture*. en. New York, New York: Columbia University Press, 2006.

[236] Rafael Morales González et al. "UltraPower: Powering Tangible & Wearable Devices with Focused Ultrasound". In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Salzburg, Austria: Association for Computing Machinery, 2021. DOI: 10.1145/3430524.3440620.

[237] Florian 'Floyd' Mueller et al. "Towards Experiencing Eating as Play". In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. Sydney NSW, Australia: Association for Computing Machinery, 2020, pp. 239–253. DOI: 10.1145/3374920.3374930.

[238] Heiko Müller et al. "Using Electrochromic Displays to Display Ambient Information and Notifications". In: *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. UbiComp/ISWC '19 Adjunct. London, United Kingdom: Association for Computing Machinery, 2019, pp. 1075–1078. DOI: 10.1145/3341162.3344844.

[239] Martin Murer. "Making Things Apart: Gaining Material Understanding". en. In: *Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS '18*. Hong Kong, China: ACM Press, 2018, pp. 497–509. DOI: 10.1145/3196709.3196806.

[240] Martin Murer, Verena Fuchsberger, and Manfred Tscheligi. "Deconstructivist Interaction Design: Interrogating Expression and Form". en. In: *Aarhus Series on Human Centered Computing* 1.1 (Oct. 2015), p. 4. DOI: 10.7146/aahcc.v1i1.21313.

[241] Martin Murer, Verena Fuchsberger, and Manfred Tscheligi. "Un-Crafting: De-Constructive Engagements with Interactive Artifacts". en. In: *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17*. Yokohama, Japan: ACM Press, 2017, pp. 67–77. DOI: 10.1145/3024969.3024993.

[242] Martin Murer et al. “Un-Crafting: Exploring Tangible Practices for Deconstruction in Interactive System Design”. en. In: *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction - TEI ’14*. Stanford, California, USA: ACM Press, 2015, pp. 469–472. DOI: 10.1145/2677199.2683582.

[243] Robert Murray-Smith. *Build A Super Simple Supercapacitor Step by Step*. YouTube. 2019. URL: https://www.youtube.com/watch?v=FUw6cZTR9yM.

[244] Teruo Nakashima et al. “Biodegradation Characteristics of Chitin and Chitosan Films”. In: *Journal of home economics* 56 (2005), pp. 889–897.

[245] Takuji Narumi. “Multi-Sensorial Virtual Reality and Augmented Human Food Interaction”. In: *Proceedings of the 1st Workshop on Multi-Sensorial Approaches to Human-Food Interaction*. MHFI ’16. Tokyo, Japan: Association for Computing Machinery, 2016. DOI: 10.1145/3007577.3007587.

[246] Takuji Narumi et al. “Augmented Reality Flavors: Gustatory Display Based on Edible Marker and Cross-Modal Interaction”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 93–102. DOI: 10.1145/1978942.1978957.

[247] Tuan D. Ngo et al. “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges”. In: *Composites Part B: Engineering* 143 (2018), pp. 172–196. DOI: https://doi.org/10.1016/j.compositesb.2018.02.012.

[248] Aditya Shekhar Nittala et al. “Multi-Touch Skin: A Thin and Flexible Multi-Touch Sensor for On-Skin Input”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018. DOI: 10.1145/3173574.3173607.

[249] Mohd Adili Norasikin et al. “SoundBender: Dynamic Acoustic Control Behind Obstacles”. In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST ’18. Berlin, Germany: Association for Computing Machinery, 2018, pp. 247–259. DOI: 10.1145/3242587.3242590.

[250] Nouryon. *Bio-based microspheres*. https://expancel.nouryon.com/news-stories/bio-based-microspheres/. 2019.

[251] Marianna Obrist et al. “Emotions Mediated Through Mid-Air Haptics”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 2053–2062. DOI: 10.1145/2702123.2702361.

[252] Yoichi Ochiai, Takayuki Hoshi, and Ippei Suzuki. “Holographic Whisper: Rendering Audible Sound Spots in Three-Dimensional Space by Focusing Ultrasonic Waves”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 4314–4325. DOI: 10.1145/3025453.3025989.

[253] Netta Ofer, Fiona Bell, and Mirela Alistar. “Designing Direct Interactions with Bioluminescent Algae”. In: *Designing Interactive Systems Conference 2021*. DIS ’21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1230–1241. DOI: 10.1145/3461778.3462090.

[254] Naoshi Ooba et al. “Unlimited Electric Gum: A Piezo-Based Electric Taste Apparatus Activated by Chewing”. In: *Adjunct Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST ’18 Adjunct. Berlin, Germany: Association for Computing Machinery, 2018, pp. 157–159. DOI: 10.1145/3266037.3271635.

[255] Modernist Pantry. *Spherification Course*. 2016.

[256] Stefano Parisi, Valentina Rognoli, and Marieke Sonneveld. “Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education”. In: *The Design Journal* 20.sup1 (2017), S1167–S1184. DOI: 10.1080/14606925.2017.1353059.

[257] Heun Park et al. “A skin-integrated transparent and stretchable strain sensor with interactive color-changing electrochromic displays”. In: *Nanoscale* 9.22 (2017), pp. 7631–7640.

[258] Jung Wook Park et al. “Exergy: A Toolkit to Simplify Creative Applications of Wind Energy Harvesting”. In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7.1 (Mar. 2023). DOI: 10.1145/3580814.

[259] Aaron N. Parks et al. “Turbocharging Ambient Backscatter Communication”. In: *SIGCOMM Comput. Commun. Rev.* 44.4 (Aug. 2014), pp. 619–630. DOI: 10.1145/2740070.2626312.

[260] Stéphanie Pasche et al. “Wearable Biosensors for Monitoring Wound Healing”. In: *Biomedical Applications of Smart Materials*. Vol. 57. Advances in Science and Technology. Freienbach, Switzerland: Trans Tech Publications Ltd, Feb. 2009, pp. 80–87. DOI: 10.4028/www.scientific.net/AST.57.80.

[261] Pat Pataranutaporn et al. “Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction”. In: *Proceedings of the Augmented Humans International Conference*. AHs ’20. Kaiserslautern, Germany: Association for Computing Machinery, 2020. DOI: 10.1145/3384657.3384783.

[262] Tatjana Pavicic et al. “Microfocused ultrasound with visualization: Consensus on safety and review of energy-based devices”. In: *Journal of Cosmetic Dermatology* 21.2 (2022), pp. 636–647. DOI: https://doi.org/10.1111/jocd.14666.

[263] M. Pershaanaa et al. “Every bite of Supercap: A brief review on construction and enhancement of supercapacitor”. In: *Journal of Energy Storage* 50 (2022), p. 104599. DOI: https://doi.org/10.1016/j.est.2022.104599.

[264] James Pierce and Eric Paulos. “Making Multiple Uses of the Obscura 1C Digital Camera: Reflecting on the Design, Production, Packaging and Distribution of a Counterfunctional Device”. en. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI ’15*. Seoul, Republic of Korea: ACM Press, 2015, pp. 2103–2112. DOI: 10.1145/2702123.2702405.

[265] James Pierce and Eric Paulos. “Second-hand interactions: investigating reacquisition and dispossession practices around domestic objects”. en. In: *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI ’11*. Vancouver, BC, Canada: ACM Press, 2011, p. 2385. DOI: 10.1145/1978942.1979291.

[266] Manuel Pietsch et al. “Biodegradable inkjet-printed electrochromic display for sustainable short-lifecycle electronics”. In: *J. Mater. Chem. C* 8 (47 2020), pp. 16716–16724. DOI: 10.1039/D0TC04627B.

[267] Ran Poliakine. *Apple’s support for wireless charging and AR are the latest signs of ‘ubiquitous computing’*. TNW. 2017. URL: https://thenextweb.com/news/apples-support-for-wireless-charging-and-ar-are-the-latest-signs-of-ubiquitous-computing (visited on 12/28/2017).

[268] Poonam et al. “Review of supercapacitors: Materials and devices”. In: *Journal of Energy Storage* 21 (2019), pp. 801–825. DOI: https://doi.org/10.1016/j.est.2019.01.010.

[269] Chiara Posarelli et al. “High-intensity focused ultrasound procedure: The rise of a new noninvasive glaucoma procedure and its possible future applications”. In: *Survey of Ophthalmology* 64.6 (2019), pp. 826–834. DOI: https://doi.org/10.1016/j.survophthal.2019.05.001.

[270] Thomas Preindl et al. “Sonoflex: Embroidered Speakers Without Permanent Magnets”. In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. UIST ’20. Virtual Event, USA: Association for Computing Machinery, 2020, pp. 675–685. DOI: 10.1145/3379337.3415888.

[271] Keep Australia Beautiful program. *Litter – How Long Does It Take to Breakdown?* Western Australia Department of Environment and Conservation. 2011. URL: https://www.kabc.wa.gov.au/library/file/Fact%20sheets/How%20long%20Fact%20sheet%20KAB.pdf (visited on 12/28/2021).

[272] Jie Qi and Leah Buechley. “Sketching in Circuits: Designing and Building Electronics on Paper”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1713–1722. DOI: 10.1145/2556288.2557391.

[273] Jie Qi et al. “Chibitronics in the Wild: Engaging New Communities in Creating Technology with Paper Electronics”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–11. DOI: 10.1145/3173574.3173826.

[274] Rinin Parambil Ramachandran and Lutz Sommer. “Printed Inductive Coil Realized using Inkjet Printing on Flexible Substrate for RFID Technology Applications”. en. In: *International Journal of Science Technology and Engineering* 4.9 (2018), p. 5.

[275] Omar Rana. *Nature’s Recipe Book*. materiom. 2018. URL: `https://materiom.org/` (visited on 09/09/2021).

[276] Nimesha Ranasinghe and Ellen Yi-Luen Do. “Digital Lollipop: Studying Electrical Stimulation on the Human Tongue to Simulate Taste Sensations”. In: *ACM Trans. Multimedia Comput. Commun. Appl.* 13.1 (Oct. 2016). DOI: `10.1145/2996462`.

[277] Nimesha Ranasinghe et al. “Digital Flavor: Towards Digitally Simulating Virtual Flavors”. In: *Proceedings of the 2015 ACM on International Conference on Multimodal Interaction*. ICMI ’15. Seattle, Washington, USA: Association for Computing Machinery, 2015, pp. 139–146. DOI: `10.1145/2818346.2820761`.

[278] Nimesha Ranasinghe et al. “Vocktail: A Virtual Cocktail for Pairing Digital Taste, Smell, and Color Sensations”. In: *Proceedings of the 25th ACM International Conference on Multimedia*. MM ’17. Mountain View, California, USA: Association for Computing Machinery, 2017, pp. 1139–1147. DOI: `10.1145/3123266.3123440`.

[279] Atomik Research. *PR Research: Oxfam – Fast Fashion*. 4media group, inc. 2020. URL: `https://www.atomikresearch.co.uk/case-studies-archive/pr-research-oxfam-fast-fashion/` (visited on 08/18/2022).

[280] Research and Markets. *Ultra-low-power Microcontroller Market by Peripheral Device (Analog Devices and Digital Devices), Packaging Type (8-bit, 16-bit, and 32-bit), End-Use Application, & Region (North America, Europe, APAC, Rest of the World) - Global Forecast to 2027*. 2022.

[281] UK Research and Innovation. *Replacing Indium Tin Oxide (ITO) with next-generation graphene in electronic devices*. 2019.

[282] Julia Ringler and Holger Reckter. “DESU 100: about the temptation to destroy a robot”. en. In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction - TEI ’12*. Kingston, Ontario, Canada: ACM Press, 2012, p. 151. DOI: `10.1145/2148131.2148164`.

[283] Valentina Rognoli et al. “DIY materials”. In: *Materials & Design* 86 (2015), pp. 692–702. DOI: `https://doi.org/10.1016/j.matdes.2015.07.020`.

[284] A. Russo et al. “Pen-on-paper flexible electronics.” In: *Advanced Materials* 23 30 (2011), pp. 3426–30.

[285] Jason D. Ryan et al. “Machine-Washable PEDOT:PSS Dyed Silk Yarns for Electronic Textiles”. In: *ACS Applied Materials & Interfaces* 9.10 (2017). PMID: 28245105, pp. 9045–9050. DOI: `10.1021/acsami.7b00530`.

[286] Kimiko Ryokai, Stefan Marti, and Hiroshi Ishii. “I/O brush: drawing with everyday objects as ink”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’04. Vienna, Austria: Association for Computing Machinery, 2004, pp. 303–310. DOI: 10.1145/985692.985731.

[287] Samar Sabie et al. “Unmaking@CHI: Concretizing the Material and Epistemological Practices of Unmaking in HCI”. In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491101.3503721.

[288] Mustafa Ergin Şahin, Frede Blaabjerg, and Ariya Sangwongwanich. “A Comprehensive Review on Supercapacitor Applications and Developments”. In: *Energies* 15.3 (2022). DOI: 10.3390/en15030674.

[289] Corina Sas and Carman Neustaedter. “Exploring DIY Practices of Complex Home Technologies”. In: *ACM Trans. Comput.-Hum. Interact.* 24.2 (Apr. 2017). DOI: 10.1145/3057863.

[290] Corina Sas, Steve Whittaker, and John Zimmerman. “Design for Rituals of Letting Go: An Embodiment Perspective on Disposal Practices Informed by Grief Therapy”. en. In: *ACM Transactions on Computer-Human Interaction* 23.4 (Sept. 2016), pp. 1–37. DOI: 10.1145/2926714.

[291] Munehiko Sato, Ivan Poupyrev, and Chris Harrison. “Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’12. Austin, Texas, USA: ACM, 2012, pp. 483–492. DOI: 10.1145/2207676.2207743.

[292] Jenn Savedge. *How to Make Leaf Skeletons*. Treehugger. 2020. URL: https://www.treehugger.com/how-make-leaf-skeletons-4868589 (visited on 05/05/2020).

[293] Energy Saver. *How Energy-Efficient Light Bulbs Compare with Traditional Incandescents*. U.S. Department of Energy. 2021. URL: https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/how-energy-efficient-light (visited on 08/29/2021).

[294] Dirk Schaefer and Wai M. Cheung. “Smart Packaging: Opportunities and Challenges”. In: *Procedia CIRP* 72 (2018). 51st CIRP Conference on Manufacturing Systems, pp. 1022–1027. DOI: https://doi.org/10.1016/j.procir.2018.03.240.

[295] Paul Scherz and Simon Monk. *Practical electronics for inventors*. Vol. 29. New York, NY, USA: McGraw-Hill, 2000.

[296] Vipul Sharma et al. “Copper Oxide Microtufts on Natural Fractals for Efficient Water Harvesting”. en. In: *Langmuir* 37.11 (Mar. 2021), pp. 3370–3381. DOI: 10.1021/acs.langmuir.0c03497.

[297] Vipul Sharma et al. “Flexible biodegradable transparent heaters based on fractal-like leaf skeletons”. en. In: *npj Flexible Electronics* 4.1 (Dec. 2020), p. 27. DOI: 10.1038/s41528-020-00091-8.

[298] Alina S. Sharova et al. “Edible Electronics: The Vision and the Challenge”. In: *Advanced Materials Technologies* 6.2 (2021), p. 2000757. DOI: https://doi.org/10.1002/admt.202000757.

[299] Vivian Shen, Craig Shultz, and Chris Harrison. “Mouth Haptics in VR Using a Headset Ultrasound Phased Array”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3501960.

[300] Ofer Shochet. *Compostable RFID antennas by leveraging nano-copper inks*. Aug. 2020.

[301] Prerna Sinha, Soma Banerjee, and Kamal K Kar. “Activated carbon as electrode materials for supercapacitors”. In: *Handbook of Nanocomposite Supercapacitor Materials II*. Cham, Switzerland: Springer, 2020, pp. 113–144.

[302] Sowmya Somanath et al. “Engaging ’At-Risk’ Students through Maker Culture Activities”. In: *Proceedings of the TEI ’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’16. Eindhoven, Netherlands: Association for Computing Machinery, 2016, pp. 150–158. DOI: 10.1145/2839462.2839482.

[303] Katherine W Song. “Decomposable Interactive Systems”. In: *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. UIST ’23 Adjunct. , San Francisco, CA, USA, Association for Computing Machinery, 2023. DOI: 10.1145/3586182.3616705.

[304] Katherine W Song and Eric Paulos. “Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI ’21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411764.3445529.

[305] Katherine W Song et al. “Füpop: ”Real Food” Flavor Delivery via Focused Ultrasound”. In: *Proceedings of the CHI Conference on Human Factors in Computing Systems*. CHI ’24. , Honolulu, HI, USA, Association for Computing Machinery, 2024. DOI: 10.1145/3613904.3642709.

[306] Katherine W Song et al. “Lotio: Lotion-Mediated Interaction with an Electronic Skin-Worn Display”. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI ’23. Hamburg, Germany: Association for Computing Machinery, 2023. DOI: 10.1145/3544548.3581098.

[307] Katherine W Song et al. “Sustainable Unmaking: Designing for Biodegradation, Decay, and Disassembly”. In: *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems*. CHI EA ’24. Honolulu HI USA: Association for Computing Machinery, 2024. DOI: 10.1145/3613905.3636300.

[308] Katherine W Song et al. “Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3502007.

[309] Katherine W. Song and Eric Paulos. “Vim: Customizable, Decomposable Electrical Energy Storage”. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI ’23. Hamburg, Germany: Association for Computing Machinery, 2023. DOI: 10.1145/3544548.3581110.

[310] Daniel Spelmezan, Rafael Morales González, and Sriram Subramanian. “SkinHaptics: Ultrasound focused in the hand creates tactile sensations”. In: *2016 IEEE Haptics Symposium (HAPTICS)*. Philadelphia, PA, USA: IEEE, 2016, pp. 98–105. DOI: 10.1109/HAPTICS.2016.7463162.

[311] Grant Stokke. *Homemade Supercapacitor Demo*. YouTube. 2017. URL: https://www.youtube.com/watch?v=3CnmuIhgn4g.

[312] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. “From Pulse Trains to ”Coloring with Vibrations”: Motion Mappings for Mid-Air Haptic Textures”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. DOI: 10.1145/3173574.3173639.

[313] David Sumner. “Measurement of electrical taste threshold”. In: *Proceedings of the Royal Society of Medicine*. Vol. 64. London, UK: SAGE Publications, 1971, pp. 658–660.

[314] A. Sydney Gladman et al. “Biomimetic 4D printing”. en. In: *Nature Materials* 15.4 (Apr. 2016), pp. 413–418. DOI: 10.1038/nmat4544.

[315] Axel Sylvester, Tanja Döring, and Albrecht Schmidt. “Liquids, Smoke, and Soap Bubbles: Reflections on Materials for Ephemeral User Interfaces”. In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’10. Cambridge, Massachusetts, USA: Association for Computing Machinery, 2010, pp. 269–270. DOI: 10.1145/1709886.1709941.

[316] Axel Sylvester, Tanja Döring, and Albrecht Schmidt. “Liquids, Smoke, and Soap Bubbles: Reflections on Materials for Ephemeral User Interfaces”. In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’10. Cambridge, Massachusetts, USA: Association for Computing Machinery, 2010, pp. 269–270. DOI: 10.1145/1709886.1709941.

[317] Ryo Takahashi et al. “Design of Cuttable Wireless Power Transfer Sheet”. In: *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. UbiComp ’18. Singapore, Singapore: Association for Computing Machinery, 2018, pp. 456–459. DOI: 10.1145/3267305.3267570.

[318] Ryo Takahashi et al. "Meander Coil++: A Body-Scale Wireless Power Transmission Using Safe-to-Body and Energy-Efficient Transmitter Coil". In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. New Orleans, LA, USA: Association for Computing Machinery, 2022. DOI: 10.1145/3491102.3502119.

[319] Ken Takaki et al. "Coil Design for Wireless Power Transfer and Communication over Hinges of Smart Glasses". In: *Proceedings of the 2020 International Symposium on Wearable Computers*. ISWC '20. Virtual Event, Mexico: Association for Computing Machinery, 2020, pp. 79–83. DOI: 10.1145/3410531.3414299.

[320] Mein Jin Tan et al. "Biodegradable electronics: cornerstone for sustainable electronics and transient applications". In: *Journal of Materials Chemistry C* 4.24 (2016), pp. 5531–5558.

[321] Theresa Jean Tanenbaum et al. "Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: Association for Computing Machinery, 2013, pp. 2603–2612. DOI: 10.1145/2470654.2481360.

[322] Hu Tao et al. "Silk-Based Conformal, Adhesive, Edible Food Sensors". In: *Advanced Materials* 24.8 (2012), pp. 1067–1072. DOI: https://doi.org/10.1002/adma.201103814.

[323] Wladyslaw Tatarkiewicz. "The Great Theory of Beauty and Its Decline". In: *The Journal of Aesthetics and Art Criticism* 31.2 (1972), pp. 165–180. DOI: 10.2307/429278.

[324] Gail ter Haar. "Therapeutic applications of ultrasound". In: *Progress in Biophysics and Molecular Biology* 93.1 (2007). Effects of ultrasound and infrasound relevant to human health, pp. 111–129. DOI: https://doi.org/10.1016/j.pbiomolbio.2006.07.005.

[325] Jordan Tewell, Jon Bird, and George R. Buchanan. "Heat-Nav: Using Temperature Changes as Navigation Cues". en. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver Colorado USA: ACM, May 2017, pp. 1131–1135. DOI: 10.1145/3025453.3025965.

[326] Jordan Tewell, Jon Bird, and George R. Buchanan. "The Heat is On: A Temperature Display for Conveying Affective Feedback". en. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver Colorado USA: ACM, May 2017, pp. 1756–1767. DOI: 10.1145/3025453.3025844.

[327] Skylar Tibbits. "4D Printing: Multi-Material Shape Change". In: *Architectural Design* 84.1 (2014), pp. 116–121. DOI: 10.1002/ad.1710.

[328] Daniel Tobjörk and Ronald Österbacka. "Paper Electronics". In: *Advanced Materials* 23.17 (2011), pp. 1935–1961. DOI: https://doi.org/10.1002/adma.201004692.

[329] Djadidi Toybou et al. "A toxicology-informed, safer by design approach for the fabrication of transparent electrodes based on silver nanowires". In: *Environ. Sci.: Nano* 6 (2 2019), pp. 684–694. DOI: 10.1039/C8EN00890F.

[330] Anka Trajkovska Petkoska et al. "Edible packaging: Sustainable solutions and novel trends in food packaging". In: *Food Research International* 140 (2021), p. 109981. DOI: https://doi.org/10.1016/j.foodres.2020.109981.

[331] Robert Triggs. *Samsung vs Huawei reverse wireless charging test*. Android Authority. 2019. URL: https://www.androidauthority.com/samsung-vs-huawei-reverse-wireless-charging-968692/ (visited on 03/26/2019).

[332] Vasiliki Tsaknaki and Ylva Fernaeus. "Expanding on Wabi-Sabi as a Design Resource in HCI". en. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose California USA: ACM, May 2016, pp. 5970–5983. DOI: 10.1145/2858036.2858459.

[333] Vasiliki Tsaknaki et al. "Things Fall Apart: Unpacking the Temporalities of Impermanence for HCI". en. In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction - NordiCHI '16*. Gothenburg, Sweden: ACM Press, 2016, pp. 1–3. DOI: 10.1145/2971485.2987680.

[334] J. Ulrich Sommer et al. "Evaluation of the maximum isometric tongue force of healthy volunteers". In: *European Archives of Oto-Rhino-Laryngology* 271.11 (Nov. 2014), pp. 3077–3084. DOI: 10.1007/s00405-014-3103-6.

[335] Muhammad Umair et al. "Exploring Personalized Vibrotactile and Thermal Patterns for Affect Regulation". en. In: *Designing Interactive Systems Conference 2021*. Virtual Event USA: ACM, June 2021, pp. 891–906. DOI: 10.1145/3461778.3462042.

[336] Amanda Freitas Valentim et al. "Evaluation of the force applied by the tongue and lip on the maxillary central incisor tooth". en. In: *CoDAS* 26.3 (June 2014), pp. 235–240. DOI: 10.1590/2317-1782/201420130077.

[337] Elzelinde Van Doleweerd and Miguel Bruns Alonso. "The Creation of a Holistic Interactive Dining Experience with Shape-Changing Food Materials at Restaurant Alchemist". In: *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '23. Warsaw, Poland: Association for Computing Machinery, 2023. DOI: 10.1145/3569009.3572791.

[338] Eldy S Lazaro Vasquez, Hao-Chuan Wang, and Katia Vega. "The Environmental Impact of Physical Prototyping: a Five-Year CHI Review". en. In: *SelfSustainableCHI 2020*. Honolulu, HI, USA: ACM, Apr. 2020, p. 8.

[339] Eldy S. Lazaro Vasquez and Katia Vega. "From plastic to biomaterials: prototyping DIY electronics with mycelium". en. In: *Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers - UbiComp/ISWC '19*. London, United Kingdom: ACM Press, 2019, pp. 308–311. DOI: 10.1145/3341162.3343808.

[340] Eldy S. Lazaro Vasquez and Katia Vega. "Myco-accessories: sustainable wearables with biodegradable materials". en. In: *Proceedings of the 23rd International Symposium on Wearable Computers - ISWC '19*. London, United Kingdom: ACM Press, 2019, pp. 306–311. DOI: 10.1145/3341163.3346938.

[341] Katia Vega, Marcio Cunha, and Hugo Fuks. "Hairware: The Conscious Use of Unconscious Auto-Contact Behaviors". In: *Proceedings of the 20th International Conference on Intelligent User Interfaces*. IUI '15. Atlanta, Georgia, USA: Association for Computing Machinery, 2015, pp. 78–86. DOI: 10.1145/2678025.2701404.

[342] Katia Vega and Hugo Fuks. "Beauty Technology: Body Surface Computing". In: *Computer* 47.4 (Apr. 2014), pp. 71–75.

[343] Katia Vega et al. "The Dermal Abyss: Interfacing with the Skin by Tattooing Biosensors". In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ISWC '17. Maui, Hawaii: Association for Computing Machinery, 2017, pp. 138–145. DOI: 10.1145/3123021.3123039.

[344] Carlos Velasco et al. "A Reflection on the State of Multisensory Human–Food Interaction Research". In: *Frontiers in Computer Science* 3 (2021). DOI: 10.3389/fcomp.2021.694691.

[345] Chi Thanh Vi et al. "TastyFloats: A Contactless Food Delivery System". In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ISS '17. Brighton, United Kingdom: Association for Computing Machinery, 2017, pp. 161–170. DOI: 10.1145/3132272.3134123.

[346] Steeven Villa et al. "Extended Mid-Air Ultrasound Haptics for Virtual Reality". In: *Proc. ACM Hum.-Comput. Interact.* 6.ISS (Nov. 2022). DOI: 10.1145/3567731.

[347] Nicolas Villar et al. "Project Zanzibar: A Portable and Flexible Tangible Interaction Platform". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–13. DOI: 10.1145/3173574.3174089.

[348] Marina Vukoje et al. "Thermochromic ink–paper interactions and their role in biodegradation of UV curable prints". In: *Cellulose* 25 (Oct. 2018). DOI: 10.1007/s10570-018-1970-5.

[349] Tiina Vuorinen et al. "Inkjet-printed graphene/PEDOT: PSS temperature sensors on a skin-conformable polyurethane substrate". In: *Scientific reports* 6 (2016), p. 35289.

[350] Dhaval Vyas and John Vines. “Making at the Margins: Making in an Under-resourced e-Waste Recycling Center”. In: *Proc. ACM Hum.-Comput. Interact.* 3.CSCW (Nov. 2019). DOI: 10.1145/3359290.

[351] Anandghan Waghmare et al. “UbiquiTouch: Self Sustaining Ubiquitous Touch Interfaces”. In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4.1 (Mar. 2020). DOI: 10.1145/3380989.

[352] Anran Wang et al. “FM Backscatter: Enabling Connected Cities and Smart Fabrics”. In: *Proceedings of the 14th USENIX Conference on Networked Systems Design and Implementation*. NSDI’17. Boston, MA, USA: USENIX Association, 2017, pp. 243–258.

[353] Guanyun Wang et al. “4DMesh: 4D Printing Morphing Non-Developable Mesh Surfaces”. en. In: *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST ’18*. Berlin, Germany: ACM Press, 2018, pp. 623–635. DOI: 10.1145/3242587.3242625.

[354] Guanyun Wang et al. “A-line: 4D Printing Morphing Linear Composite Structures”. en. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI ’19*. Glasgow, Scotland Uk: ACM Press, 2019, pp. 1–12. DOI: 10.1145/3290605.3300656.

[355] Jingchun Wang et al. “Biomimetic Shape–Color Double-Responsive 4D Printing”. en. In: *Advanced Materials Technologies* 4.9 (Sept. 2019), p. 1900293. DOI: 10.1002/admt.201900293.

[356] Shan Wang, Aolin Lu, and Chuan-Jian Zhong. “Hydrogen production from water electrolysis: role of catalysts”. In: *Nano Convergence* 8.1 (Feb. 2021), p. 4. DOI: 10.1186/s40580-021-00254-x.

[357] Xu Wang et al. “Food-Materials-Based Edible Supercapacitors”. In: *Advanced Materials Technologies* 1.3 (2016), p. 1600059. DOI: https://doi.org/10.1002/admt.201600059.

[358] Yan Wang et al. “Toward Understanding Playful Beverage-Based Gustosonic Experiences”. In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6.1 (Mar. 2022). DOI: 10.1145/3517228.

[359] Yan Wang et al. “WeScream! Toward Understanding the Design of Playful Social Gustosonic Experiences with Ice Cream”. In: *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. DIS ’20. Eindhoven, Netherlands: Association for Computing Machinery, 2020, pp. 951–963. DOI: 10.1145/3357236.3395456.

[360] Yanan Wang et al. “AnimSkin: Fabricating Epidermis with Interactive, Functional and Aesthetic Color Animation”. In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS ’17. Edinburgh, United Kingdom: Association for Computing Machinery, 2017, pp. 397–401. DOI: 10.1145/3064663.3064687.

[361] Yanan Wang et al. "AnimSkin: Fabricating Epidermis with Interactive, Functional and Aesthetic Color Animation". In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS '17. Edinburgh, United Kingdom: ACM, 2017, pp. 397–401. DOI: 10.1145/3064663.3064687.

[362] Yanan Wang et al. "SKIN+: Fabricating Soft Fluidic User Interfaces for Enhancing On-Skin Experiences and Interactions". In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada: Association for Computing Machinery, 2018. DOI: 10.1145/3170427.3188443.

[363] Mary M. Warnock et al. "Biodegradation of Three Cellulosic Fabrics in Soil". In: *Summaries of Arkansas Cotton Research*. Fayetteville, AR, USA: The Arkansas Agricultural Experiment Station, 2009, pp. 208–211.

[364] Martin Weigel et al. "iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2991–3000. DOI: 10.1145/2702123.2702391.

[365] Martin Weigel et al. "SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 3095–3105. DOI: 10.1145/3025453.3025704.

[366] Martin Weigel et al. "SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics". In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 3095–3105. DOI: 10.1145/3025453.3025704.

[367] Jennifer Weiler et al. "Mycelium Artifacts: Exploring Shapeable and Accessible Biofabrication". en. In: *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion - DIS '19 Companion*. San Diego, CA, USA: ACM Press, 2019, pp. 69–72. DOI: 10.1145/3301019.3325156.

[368] Mark Weiser. "The computer for the 21st century". In: *Scientific american* 265.3 (1991), pp. 94–104.

[369] Robert S Weiss. *Learning from strangers: The art and method of qualitative interview studies*. New York, NY, USA: Simon and Schuster, 1995.

[370] William Philip Werschler and Pam Schell Werschler. "Long-term Efficacy of Micro-focused Ultrasound with Visualization for Lifting and Tightening Lax Facial and Neck Skin Using a Customized Vectoring Treatment Method". In: *The Journal of Clinical and Aesthetic Dermatology* 9.2 (Feb. 2016), pp. 27–33.

[371] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. "Stretchis: Fabricating Highly Stretchable User Interfaces". In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 697–704. DOI: 10.1145/2984511.2984521.

[372] Christian J. A. M. Willemse, Dirk K. J. Heylen, and Jan B. F. van Erp. "Warmth in affective mediated interaction: Exploring the effects of physical warmth on interpersonal warmth". en. In: *2015 International Conference on Affective Computing and Intelligent Interaction (ACII)*. Xi'an, China: IEEE, Sept. 2015, pp. 28–34. DOI: 10.1109/ACII.2015.7344547.

[373] Graham Wilson and Stephen A. Brewster. "Multi-moji: Combining Thermal, Vibrotactile & Visual Stimuli to Expand the Affective Range of Feedback". en. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Denver Colorado USA: ACM, May 2017, pp. 1743–1755. DOI: 10.1145/3025453.3025614.

[374] Graham Wilson, Gavin Davidson, and Stephen A. Brewster. "In the Heat of the Moment: Subjective Interpretations of Thermal Feedback During Interaction". en. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. Seoul Republic of Korea: ACM, Apr. 2015, pp. 2063–2072. DOI: 10.1145/2702123.2702219.

[375] Graham Wilson, Dobromir Dobrev, and Stephen A. Brewster. "Hot Under the Collar: Mapping Thermal Feedback to Dimensional Models of Emotion". en. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. San Jose California USA: ACM, May 2016, pp. 4838–4849. DOI: 10.1145/2858036.2858205.

[376] Graham Wilson et al. "Perception of Ultrasonic Haptic Feedback on the Hand: Localisation and Apparent Motion". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1133–1142. DOI: 10.1145/2556288.2557033.

[377] Patrick M. Winter et al. "Initial investigation of a novel noninvasive weight loss therapy using MRI-Guided high intensity focused ultrasound (MR-HIFU) of visceral fat". In: *Magnetic Resonance in Medicine* 76.1 (2016), pp. 282–289. DOI: https://doi.org/10.1002/mrm.25883.

[378] Anusha Withana, Daniel Groeger, and Jürgen Steimle. "Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output". In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST '18. Berlin, Germany: Association for Computing Machinery, 2018, pp. 365–378. DOI: 10.1145/3242587.3242645.

[379] Bob G. Witmer and Michael J. Singer. "Measuring Presence in Virtual Environments: A Presence Questionnaire". In: *Presence: Teleoperators and Virtual Environments* 7.3 (June 1998), pp. 225–240. DOI: 10.1162/105474698565686.

[380] Paul Worgan and Mike Fraser. "CoilMove: An Actuated to-Body Energy Transfer System". In: *Proceedings of the 2017 Conference on Designing Interactive Systems*. DIS '17. Edinburgh, United Kingdom: Association for Computing Machinery, 2017, pp. 791–795. DOI: 10.1145/3064663.3064693.

[381] Shanel Wu and Laura Devendorf. "Unfabricate: Designing Smart Textiles for Disassembly". en. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, Apr. 2020, pp. 1–14. DOI: 10.1145/3313831.3376227.

[382] Yingzhu Wu et al. "Edible and Nutritive Electronics: Materials, Fabrications, Components, and Applications". In: *Advanced Materials Technologies* 5.10 (2020), p. 2000100. DOI: https://doi.org/10.1002/admt.202000100.

[383] Humphrey Yang et al. "Freeform Fabrication of Fluidic Edible Materials". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. DOI: 10.1145/3411764.3445097.

[384] Peihua Yang et al. "Printed Zinc Paper Batteries". In: *Advanced Science* 9.2 (2022), p. 2103894. DOI: https://doi.org/10.1002/advs.202103894.

[385] Yiran Yang and Wei Gao. "Wearable and flexible electronics for continuous molecular monitoring". In: *Chemical Society Reviews* 48.6 (2019), pp. 1465–1491.

[386] Lining Yao et al. "bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces". en. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. Seoul, Republic of Korea: ACM Press, 2015, pp. 1–10. DOI: 10.1145/2702123.2702611.

[387] Shanshan Yao et al. "A wearable hydration sensor with conformal nanowire electrodes". In: *Advanced healthcare materials* 6.6 (2017), p. 1601159.

[388] Huizhong Ye et al. "Body-Centric NFC: Body-Centric Interaction with NFC Devices Through Near-Field Enabled Clothing". In: *Designing Interactive Systems Conference*. DIS '22. Virtual Event, Australia: Association for Computing Machinery, 2022, pp. 1626–1639. DOI: 10.1145/3532106.3534569.

[389] Lan Yin et al. "Dissolvable Metals for Transient Electronics". In: *Advanced Functional Materials* 24.5 (2014), pp. 645–658. DOI: https://doi.org/10.1002/adfm.201301847.

[390] ynvisible. *Printed Electrochromic Displays*. 2022.

[391] Chia-Chen Yu et al. "A Conformable Ultrasound Patch for Cavitation-Enhanced Transdermal Cosmeceutical Delivery". In: *Advanced Materials* 35.23 (2023), p. 2300066. DOI: https://doi.org/10.1002/adma.202300066.

[392] Pengyu Zhang et al. "Enabling Practical Backscatter Communication for On-Body Sensors". In: *Proceedings of the 2016 ACM SIGCOMM Conference*. SIGCOMM '16. Florianopolis, Brazil: Association for Computing Machinery, 2016, pp. 370–383. DOI: 10.1145/2934872.2934901.

[393] Pengyu Zhang et al. "HitchHike: Practical Backscatter Using Commodity WiFi". In: *Proceedings of the 14th ACM Conference on Embedded Network Sensor Systems CD-ROM*. SenSys '16. Stanford, CA, USA: Association for Computing Machinery, 2016, pp. 259–271. DOI: 10.1145/2994551.2994565.

[394] Xiaopan Zhang et al. "Sustainable and Transparent Fish Gelatin Films for Flexible Electroluminescent Devices". In: *ACS Nano* 14.4 (2020). PMID: 32186191, pp. 3876–3884. DOI: 10.1021/acsnano.9b09880.

[395] Yang Zhang et al. "Sozu: Self-Powered Radio Tags for Building-Scale Activity Sensing". In: *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. UIST '19. New Orleans, LA, USA: Association for Computing Machinery, 2019, pp. 973–985. DOI: 10.1145/3332165.3347952.

[396] Ziyang Zhang et al. "Stretchable Transparent Wireless Charging Coil Fabricated by Negative Transfer Printing". In: *ACS Applied Materials & Interfaces* 11.43 (2019). PMID: 31589402, pp. 40677–40684. DOI: 10.1021/acsami.9b14728.

[397] ZMorph. *Thick Paste Extruder*. https://zmorph3d.com/products/toolheads/thick-paste-extruder. Accessed: 2020-09-10. 2020.

[398] Amit Zoran and Leah Buechley. "Hybrid Reassemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness". en. In: *Leonardo* 46.1 (Feb. 2013), pp. 4–10. DOI: 10.1162/LEON_a_00477.

[399] Amit Zoran and Dror Cohen. "Digital Konditorei: Programmable Taste Structures Using a Modular Mold". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–9. DOI: 10.1145/3173574.3173974.