Citizen science publics: nurturing science practice outside of professional settings through HCI and design

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Abstract

Citizen science broadly refers to the tools, methods, and practices by which people participate in science outside of professional settings. Over the past few decades, breakthroughs in DIY (do it yourself) methods, low-cost technologies, and social media platforms have given rise to many citizen science communities, engaging in science practice in new and often unexpected ways. These range from collecting and analyzing environmental data with off-the-shelf sensors, to communicating professional research to policy makers or members of the general public, or experimenting with biology concepts in art studios, garages, and hackspaces.

My dissertation examines citizen science initiatives as collective efforts to construct knowledge and address issues. I frame this space in terms of *publics*—groups of people who come together around shared concerns and work towards changing the status quo. In the context of citizen science, these concerns may revolve around some of the greatest challenges of our lives: healthcare, environmental pollution, food production, climate change, or the mechanisms by which professional science operates. Citizen science efforts impact these issues, whether by legitimizing new forms of science making, influencing health and environmental policy, shifting public opinion, or transforming professional science agendas.

I present four areas where Human Computer Interaction (HCI) and design can productively engage with citizen science publics. In short, these are: 1) expressing matters of concern; 2) gathering local and expert knowledge; 3) making hybrid systems; and 4) impacting science practice in and out of professional settings. I contribute to HCI by presenting functional systems, among them place-based sensors and DIY platforms for expressing concerns, and hybrid sensing systems that incorporate organic, analog, and digital materials. More broadly, I draw on ethnographically-oriented fieldwork and methods from critical making and speculative and reflective design to examine the mechanisms by which citizen science publics operate. By understanding the conditions—technological and social—that expand science practice beyond professional settings, I offer touchpoints where HCI and design research can be applied to enable grassroots innovation to occur.

1 Introduction

Citizen science broadly refers to the tools, methods, and practices by which people participate in science outside of professional settings. This phenomenon is not new. For centuries, people have participated in science without wearing a lab coat, whether by experimenting with different strands of domesticated plants, culturing bacteria through fermentation, modifying everyday tools, inferring weather patterns, or observing planets in the sky.

Over the past few decades, breakthroughs in DIY (do it yourself) methods, low-cost technologies, and social media platforms have given rise to a range of citizen science communities, engaging in science practice in new, often unexpected ways. Some groups are collecting and analyzing data with off-the-shelf sensors in an effort to monitor local factors such as air pollution or water quality (*e.g.*, Kim et al., 2011; Willet et al., 2010). Others operate as mediators between professional researchers and policy makers or the general public at large, as do for instance, the groups who communicate the impact of certain industries on health or environment[1]. Some groups coalesce around shared genetic conditions (*e.g.*, Huntington's disease[2]) and work on advocacy initiatives to raise awareness and support professional research in their field of interest. Others are experimenting with scientific concepts in art studios, garages, or hackspaces[3], thereby bringing the practices of institutional science into question or moving science work out of professional settings altogether.

Although these emerging practices involve different people, values, and desired futures, they are similar in several key ways. First and foremost, groups of citizen scientists are often brought together by shared concerns. These concerns may revolve around divisive issues, ones that have lasting implications, and not only for the people directly involved: healthcare, environmental policy, or the mechanisms by which professional science operates. In the process of navigating these issues, various groups of stakeholders coalesce into *publics*—cohesive groups that discuss and work towards resolving shared concerns (Dewey, 1927). A heterogeneous set of methods and materials—often hybrid assemblies of sensing technologies, social media platforms, analog tools, living organisms, and even the human bodies themselves—is drawn upon to construct, communicate, and pluralize scientific knowledge. Finally, with these assemblies, citizen science publics work to change the status quo. Whether by legitimizing new forms of science making through

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[1] For example, Marcellus Protest, http://www.marcellusprotest.org/
[2] Huntington's Disease Society of America. http://www.hdsa.org
[3] An Institution for the Do-It-Yourself Biologist, DIYbio.org

collaborations with professionals, influencing health and environmental policy, shifting public opinion, or transforming the mechanisms that motivate professional institutions, citizen science initiatives can have broad and lasting impact.

1.1 Motivation

My dissertation examines the social, political, and technological materials and practices of citizen science publics from the perspective of HCI (Human Computer Interaction) and design. My research is motivated by the blurring of boundaries between professional and amateur science making. In today's increasingly connected world, stakeholders who are not professional scientists—from regulatory bodies and corporations, to hobbyists, artists, and activists—are influencing science policy, funding, and agendas. Citizen science communities, which often operate as intermediaries between professional researchers and the general public at large, not only serve to interpret, contest, and contribute to scientific knowledge, but also work towards changing the way professional research is produced and disseminated. Simply put, these bottom-up initiatives have the potential to democratize and transform how science is done.

Alongside this trajectory of public participation in science, it is important to note that scientific inquiry has often been radically innovated by ideas and breakthroughs from outside the laboratory. The accidental discovery of penicillin, or the adoption of a jam ingredient, agar, as a growth medium are case and point. With many citizen science movements revolving around some of the most pressing challenges of our lives, from healthcare and environmental sustainability, to the global food and water crisis, or the production of sustainable energy, participation from outside of professional settings is too important to be ignored. By understanding the conditions—technological and social—that expand science practice beyond professional settings, HCI and design research can be applied to enable grassroots innovation to occur.

1.1.1 Citizen science publics and HCI

HCI, a field that is increasingly focused on systems that empower, democratize, and educate, has a lot to contribute to the formation, practices, and outcomes of citizen science publics. Indeed, HCI is seeing a surge of research that supports scientific participation and sharing—from platforms for collecting observations and measurements, to crowdsourced sensing and computing, and novel data analysis tools (*e.g.*, Iacovides et al., 2013; Irwin, 1995; Paulos et al., 2008; Reddy et al., 2004; Willet et al., 2010; etc.). In parallel, HCI work is increasingly focusing on values and issues, including research in emphatic, feminist, value-sensitive, speculative, participatory, and adversarial design—the types of approaches that involve stakeholders from the bottom up in ideating, materializing, and critiquing possible desired futures (*e.g.*, Bardzell, 2010; Friedman et al., 2006; Gaver et al., 2003; DiSalvo, 2014; Hayes, 2011; and others). With these trajectories in HCI and design research as a backdrop, my dissertation broadly ask, how can HCI and design support science practice and communities outside of professional settings?

1.2 Research questions and goals

In my work, I examine four areas where HCI can productively engage with citizen science publics. In short, these are: 1) expressing matters of concern; 2) gathering local and expert knowledge; 3) making hybrid systems; and 4) having broader impact by enabling groups to transform science practice in and out of professional settings.

The first of these effectively addresses the beginnings of citizen science movements—how people are made aware of and assemble around shared issues. Drawing on HCI work in political design, spectacle computing, and DIY research, I present several functional systems and DIY platforms that enable stakeholders to express matters of concern. The second area explores the mechanisms by which communities with varying degrees of expertise gather information and co-produce lay-expert knowledge. Grounded in existing participatory sensing research and ethnographically-oriented fieldwork methodology, I focus on how knowledge is gathered by people who rely on living systems to infer environmental information. Third, I examine the artifacts that give physical form to citizen science knowledge and concerns. Adopting the framework of seamful computing, I integrate organic, analog, and digital materials into the design of sensing systems that materialize environmental processes and issues. Finally, I turn to bottom-up movements and technologies that are transforming science practice itself. Specifically, I highlight the emerging intersections between biology, computation, and public engagement with what has been traditionally considered 'lab science'. I report on the practices and tools of DIYbio (Do It Yourself Biology) and genetics communities to envision how HCI techniques can be applied to empower scientific literacy and agency across these emerging groups.

With the above four areas thus outlined, my dissertation addresses the following questions:

- What new interactive systems and paradigms can enable people to express matters of concern?
- How is local knowledge gathered, made sense of, and shared amongst citizen science practitioners?

- What role do materials—from digital to analog and organic—play in constructing knowledge and articulating concerns?
- How can new information technologies enable groups to transform biology and genetics research within and outside of professional institutions?

To address these questions, I present my research across four themes: (1) expressing concerns though place-based sensing and tangible media (2) a case study of local knowledge production through the use of organic systems as environmental sensors, (3) the design and deployment of hybrid systems that leverage non-digital inputs and outputs, and (4) studies of and design prototypes around public participation in genetics and biology.

1.3.2 Contributions to HCI

My overarching goal is to unpack how citizen science communities operate and the mechanisms by which their work feeds back into and transforms professional research. The sociotechnical practices and materials of citizen science communities serve as productive touchpoints for HCI, and I explore these through fieldwork, physical prototyping, and deployment of systems. My work is informed by academic disciplines in design, computer science, and philosophy of technology, as well as environmental science, ecology, and biology. I rely on ethnographically-oriented fieldwork to develop deep insights into technological practices of stakeholders—from urban communities of grassroots activists, hackers, and makers, to professional scientists and everyday citizens such as cyclists, parents, or the homeless. Drawing on methods from critical making and speculative and reflective design, I prototype functional systems that explore potential future states for citizen science practice. With physical prototyping as a key element of my work, I study the political and social implications of digital artifacts as they are deployed to and appropriated by stakeholders.

This dissertation offers several key contributions to HCI. First, from a purely technical point of view, I present the design and deployment of several novel functional systems, including: a networked system of place-based air quality sensors that enabled four urban communities to track air pollution in real time; new visualizations of environmental data through spectacle computing; and environmental monitoring systems that draw on concepts from biology and design research to incorporate organic and digital materials into hybrid assemblies. These technical contributions explore opportunity areas identified by my *in-situ* fieldwork and workshops with communities of practice. More broadly, I contribute to HCI by 1) reframing sensors from passive instruments of data collection, and towards expressive tools for community activism around local issues; 2) studying and designing systems that rely on organic materials as part of the sensing process; and 3) examining new interactive systems for public participation in biology and genetics. My work thus serves to expand HCI citizen science research beyond the development of digital data collection platforms, and towards supporting deeper engagements with the physical world.

1.3.1 Organization

I continue by critically examining how citizen science publics form and operate. I draw on related work in design, HCI, and science studies, along with examples from the real world citizen science initiatives, to discuss the practices, tools, goals, and challenges of citizen science publics. The four areas I identified earlier—expressing concerns, gathering knowledge, making hybrid systems, and transforming science practice—serve as focal points for my literature review. Chapters 3 and 4 present HCI strategies and systems for expressing matters of concern. In Chapter 3, I introduce place-based sensing as an approach for supporting discourse around community issues. As part of this work, I detail the design of networked air quality sensors that were shared by groups of homeless, parents, bicyclists and activists. Chapter 4 adopts strategies from spectacle computing to the design of DIY platforms that vibrantly project ideas into the public sphere. As part of this chapter, I report on existing public expression practices through a study of street artists and activists and present two DIY platforms—WallBots and air quality balloons—that enable stakeholders to author public spaces with matters of concern.

Shifting from placing and making sensors, Chapter 5 critically re-examines HCI's understanding of sensing systems and the methods by which local knowledge is gathered. I report on the practices of individuals who rely on biomarkers to infer environmental information as a case study of local knowledge production, and propose integrating organic and living materials into environmental sensing systems. Chapter 6 explores hybrid materials more deeply through the design of two systems that integrate organic, analog, and digital elements as inputs and outputs. As part of that work, I present the design and deployment of paper-based approach for monitoring particulate pollution and a bio-electronic system that visualizes progress of micro-organisms in soil. Finally, Chapters 7 and 8 focus on the intersection between biology, computation, and public engagement with science. Chapter 7 examines open participation in biology: first, by presenting the practices and materials of the DIYbio (Do It Yourself biology) movement, and second, by reporting on my work with DIY kits for performing genetic tests outside of professional settings. Finally, Chapter 8 offers insights into public participation in personal genetics through the study of 23andMe, an online genetic testing service and communities. I conclude by summarizing my contributions, and discussing future challenges and opportunities for interaction design.

2 Citizen science publics

Shortly after the North River Sewage Treatment plant opened in April of 1986, West Harlem residents began reporting foul odors, along with symptoms of respiratory illness—shortness of breath, irritated throat, watery eyes. By 1988, West Harlem had one of the highest incidences of childhood asthma hospitalizations in the nation. In an effort to draw attention to this "growing epidemic", the residents first employed "community mobilization tactics". For instance, on January 15, 1988 (Martin Luther King Day), community members, outfitted with gas masks and placards, gathered along Riverside Drive to stop traffic in an effort to "dramaticize the unbearable situation"[4]. Yet the plant continued to operate.

The residents then formed WE ACT (West Harlem Environmental Action)—an advocacy group for Environmental Justice. The organization mobilized local youths to map areas where they experienced onsets of asthma and symptoms of respiratory illnesses. The resulting "risk maps" showed these self-reports along with air quality data from the EPA. WE ACT then partnered with scientists at Columbia University's Center for Environmental Health and conducted two studies, examining exposure levels to diesel fumes through urinary analysis at two local schools; and measuring air quality with personal and stationary monitors, specifically focusing on the pollution hot spots identified by the "risk maps". This research was presented to the EPA, resulting in policy changes to tighten air quality standards, as well as a 1.1 million dollar settlement with the New York City Department of Environmental Protection[5].

The story of WE ACT, despite its unique circumstances, is not unlike other bottom-up initiatives, whereby stakeholders come together around a shared issue and enact change. From the citizens' concerns, initially ignored by authorities despite public dramatizations of the situation, to the early findings from local self-reports, to the collaborative studies with professional scientists, and finally, the eventual impact on public policy, aspects of this story reflect a broad arc within citizen science movements. These themes—expressing concerns, gathering knowledge, creating artifacts, and enacting change—have been the subject of a growing body of research within and outside of HCI. In what follows, I review related HCI and design work around these areas, referring back to WE ACT's story as a way of illustrating how these processes unfold in the real world.

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[4] WE ACT for Environmental Justice. http://www.weact.org/tabid/180/Default.aspx
[5] History of WE ACT. http://www.weact.org/Home/WEACTHistory/tabid/180/Default.aspx

2.1 Expressing matters of concern

Even before the sewer plant began operating, other air-polluting factors, among them several Bus Depots and excessive traffic, were already at play in West Harlem. The opening of the plant, however, made the situation "unbearable", resulting in an organized research and advocacy effort by the residents. The EPA air quality data, traffic patterns, and Bus Depot Locations, along with local reports of respiratory illness, transformed from matters of fact into *matters of concern*.

The difference between matters of fact and matters of concern is this: matters of fact are calculable, reproducible products of "hard" science; matters of concern are value constructions around these facts. Simply put, matters of concern are science facts put into context, encompass not only scientific data, but also the social, economic, and political experiences around it (Latour, 2005). Accepting matters of fact is problematic because, as Latour points out, "*transparent, unmediated, undisputable facts have recently become rarer and rarer*" (2005). This is, in part, due to the blurring of boundaries between who operates within and outside of science, with lab workers, corporations, and politicians all influencing research agenda in different ways (Latour, 1987). Even the EPA air quality sensor data, for instance, can be dismissed by some as biased, inaccurate, unrepresentative, or irrelevant. Facts concerning people on a larger scale—*e.g.*, climate change research—are even more contested still (*ibid*). When people begin to contextualize and critique scientific findings within their own observations and experiences, the incalculable aspects of the situation are brought to light, giving rise to matters of concern.

As with the dialogues amongst residents, professional scientists, and policy makers in West Harlem, matters of concern can give rise to publics (Dewey, 1927). Simply put, citizens become aware of pressing issues and work together to resolve them (Dewey, 1927). According to Dewey, modern culture of consumption and quick gratification (i.e. "the movie, radio, cheap reading matter and motor car") inadvertently distracts people by providing an "easy and cheap" entertainment (Dewey, 1927). Indeed, the role that technology plays in fostering scientific and political discourse continues to be widely debated throughout design literature (*e.g.*, Ananny et al., 2004). For instance, Irwin and Chang et al. separately argue that public awareness of pressing issues is hindered by "rational ignorance": people succumb to apathy if the efforts to educate oneself about an issue outweigh any possible changes that can be achieved by the individual (Chang et al., 2005; Irwin, 1995). At the same time, HCI and design offer many productive avenues for expressing matters of concern and supporting publics.

2.1.1 Expressing concerns through design

Over the past few decades, numerous trajectories in design research—among them critical design, reflective design, participatory design, feminist HCI, value sensitive design, design fiction, and adversarial design, to name a few—have been discussed in the context of expressing stakeholder concerns and contesting the status quo (Dunne et al., 2001; Bardzell et al., 2013; Sengers, 2005; Friedman et al., 2006; DiSalvo, 2012, Bardzell, 2010, Bleeker, 2009 and others). While a detailed review of these is outside the scope of this dissertation, it is worth highlighting *pluralism* as a key principle.

Pluralism

The concept of pluralism is discussed across a range of disciplines from political philosophy, to science studies, and epistemology. Simply put, a pluralistic approach allows for multiple interpretations, values, or power influences to exist. This approach offers an alternative to methodologies that aim to establish a single, "correct" interpretation. Within interaction design, Suchman (2002) draws on feminist theory to argue for systems that transparently reveal multiple values and power structures between stakeholders. Likewise importing feminism into HCI, Bardzell argues for "design artifacts that resist any single, totalizing, or universal point of view" (Bardzell, 2010). In the same vein, Sengers and Gaver (2006) suggest that multiple meanings can fruitfully co-exist between user, system, and designer, and Gaver et al., (2003) has presented design strategies that embrace ambiguity. Specifically addressing design for constructing publics, DiSalvo (2005) emphasizes projection—presenting "future consequences associated with an issue" and tracing—exposing the hybrid "networks of materials, actions, concepts and values that shape and frame an issue over time". In his later work, DiSalvo (2012) also illustrates how agonistic pluralism can create productive conflict and/or enable tools and spaces for contesting the status quo.

Although pluralism is discussed in different design contexts within this literature, the trend is to depart from the dominant idea that systems should convey single, authoritative "facts". This stance diverges from the more traditional emphasis on calibrations, error rates, and efficiency as success metrics for new technologies in HCI. For instance, a pluralist approach offers an alternative to visualizations that facilitate specific judgments about the world: 'traffic light' metaphors convey that air quality is either good or bad, graphs and numeric displays draw attention to high/low values (*e.g.*, Willet et al., 2010; Reddy, 2004; Maisonneuve, 2009; Eisenman, 2009; Dillahunt, 2009 and others). While systems that quantify our world are undoubtedly useful, design that materializes diverse interests, value systems, and power structures might be more aligned with what transforms ordinary citizens into cohesive publics: expressing matters of concern.

Community engagement and action research

In addition to theoretical perspectives, design work has collaboratively engaged with stakeholders through action research (Hayes 2011). A variety of methods have been explored: participatory co-design to express tensions between residents and caretakers at a homeless shelter (LeDantec et al., 2010); co-design and prototyping workshops to discuss issues in a neighborhood (DiSalvo et al., 2009); participatory design to reveal public concerns around infrastructure development (Clement et al., 2012); pastiche scenarios to help users articulate critique technologies through fictional narrative (Blythe et al., 2006); value-driven design to reveal points of tension across an e-government system (Voida et al., 2014). These approaches illustrate how design researchers can involve communities in identifying and articulating concerns from the bottom up.

2.1.2 Expressive technologies and spectacles

HCI has also seen a surge of new technologies for public expression. These range from the playful SoundMites (Bouchard et al., 2007) and LED Throwies[6], which enable users to leave interactive audio and video nodes on public surfaces, to the more speculative air quality sensors deployed on robotic dogs (Jeremijenko et al., 2009) and live homing pigeons (DaCosta et al., 2006). Specifically in the context of environmental sensing, public visualizations include Kim et al.'s WearAir (2009)—a T-shirt that responds air quality with interactive lights, CO2RSET—a corset that constricts when the air becomes toxic (OFriel, 2008), the pollution e-sign, which hijacks passerby's mobile phones with air quality data (Hooker et al., 2007), and Air de Paris Balloon—a giant balloon tethered over the city of Paris to show data collected from several sensing stations (Aerophile, 2008). To varying degrees, these systems trend towards vibrantly projecting ideas into the public sphere and pave a trajectory for creating spectacles—not unlike West Harlem residents' early initiative to dramatically halt traffic along a major highway to draw attention to their situation.

Spectacle computing

Artists have a long history of integrating "the spectacle" into their work: from Allan Kaprow's Happenings (1996) and the writings of Guy Debord (1994) and the Situationists in the 1960's, to more contemporary tactical media artists such as The Yes Men, Critical Art Ensemble, RTMark, Preemptive Media, and Institute for Applied Autonomy. The Situationists differentiated between passive subjects—consumers of the spectacle—and those who transform their own ideas, concerns, and passions into the spectacle itself. This movement applied concepts of commodity fetishism (Marx, 1867) to contemporary mass media to expose the common politics of its day. Recently, Leahu et al. (2008) discuss how Situationist ideas have been (sometimes carelessly) imported into HCI. Specifically, the authors argue that while improvisational and public Situationist tactics are

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8 Graffiti Research Lab. Throwies. http://graffitiresearchlab.com/?page_id=6 (accessed 2013).

frequently employed by art practice within HCI, a thorough discussion of the movement's political and social stance is omitted. Along the same lines, DiSalvo (2012) distinguishes between provocations—dramatizations of a situation, and spectacles—dramatic events that support substantive reflections. Thus, while many HCI technologies can and do enable public expression, *spectacle computing* aims to present issues as a way of igniting debate about the present situation and re-imaging potential futures (Kuznetsov et al., 2011).

In this section, I have focused on matters of concern as the starting point for publics. Using the coalescing of residents, scientists, and policy makers around issues of air quality in West Harlem as an example, I have outlined the processes by which divisive issues can bring publics into being. I then discussed several ways by which design and HCI have been used to express concerns: embracing pluralism in design; action research with communities; and technological interventions that enable public expressions and trend towards spectacle computing. My own work contributes to this area in Chapters 3 and 4, where I reframe sensing as an output modality for projecting community concerns into the public sphere and present several DIY technologies for creating spectacles.

2.2 Gathering local and expert knowledge

Turning back West Harlem for another brief moment, recall that when WE ACT first formed in 1988, residents began systematically documenting onsets of their respiratory problems, as well as foul odors, traffic patterns, and other observations about the environment. This information was used as a starting point for collaborating with Columbia University Scientists. The emerging community of scientists and residents then monitored air quality at the pollution hot spots and traced exposure to diesel by analyzing residents' urine. Personal experiences, observations, and intuitions were gathered and combined with findings from research studies, resulting in co-production of knowledge and expertise.

Coburn (2005) sets out to conceptualize local knowledge as a heterogeneous "set of narratives, tools, and practices located in a particular place, culture or community". Of course, with today's increasing connectivity between people and ideas, "local" does not necessarily pertain to a particular geographic region, but rather a particular social context or group of people. This type of knowledge offers what Coburn calls "oppositional discourse"—an alternative, though not necessarily opposing, perspective to conventional science. In some cases, as with the information gathered by WE ACT, local knowledge productively contextualizes and contributes to professional research. Other times—as with, for instance, health advocacy groups who report on experiences of living with certain genetic conditions—local knowledge also interprets and sometimes critiques scientific findings. Moreover, local knowledge can serve to problematize the mechanisms by which expert research is conducted and communicated, as is done by DIYbio (Do It Yourself biology) initiatives that aim to 'open source' biology. These three domains—environmental science, biology, and genetics—offer unique insights into how local and expert knowledge is gathered and are increasingly becoming the subject of HCI and design inquiries.

2.2.1 Platforms for collecting local knowledge

This story of WE ACT resonates with many citizen science projects that aggregate local knowledge and professional research. Other well-known examples include the Christmas Birdcount[7]—volunteer-driven bird census, and Project Budburst[8]—citizen-based monitoring of plant phenophases, and myriad other initiatives, which combine local knowledge with scientific analysis to study ecosystems and track climate change. Such efforts have been of particular inspiration to HCI. Participatory sensing, as first discussed by Burke et al. (2006), is a growing area of research focusing on the mechanisms by which individuals in the general public collect, share, and analyze local data.

Participatory sensing

From sensor-equipped mobile phones and hand-held monitors, to sensors deployed in public spaces or on moving vehicles, HCI systems are enabling users to monitor factors such as air pollution, water flow in creeks, and metal content in soil. For instance, prior work employed sensor and GPS-enabled mobile phones to monitor traffic (Campbell et al., 2006) or noise pollution (Maisonneuve, 2009), share nutritional choices (Reddy et al., 2007), and document damaged sidewalks (Reddy et al., 2004). Personal data logging platforms have also been used to monitor environmental factors such as air quality (Cuff et al., 2008; Honicky et al., 2008), or support reflections on geo-tagged photographs and annotations (Prieto, 2008).

In addition to these personal technologies, public sensors have been deployed on fixed surfaces or in bounded spaces. For example, Aoki et al., (2009) attached air quality monitors on street sweepers, while Eisenman *et al.,* (2009) developed environmental sensing platforms for urban bicycles. Other factors such as soil quality and water pollution have been monitored using distributed sensor networks embedded in the physical environment (Ramanathan et al., 2009; Goldman, et al, 2007).

Technologies that enable users to measure aspects of the environment can be extremely valuable, especially in cases directly involving human health (*e.g.*,

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[7] Christmas Bird Count, http://birds.audubon.org/christmas-bird-count
[8] Project BudBurst, http://budburst.org/

detecting toxin levels in a water supply). However, recent critiques of sensing technologies have also drawn attention to how purely technological solutions may potentially bar users from engaging with important issues (*e.g.*, Brynjarsdottir et al., 2012). For instance, Leshed et al. (2008) critically investigate how GPS navigation systems can disengage people from the environments through which they navigate. Likewise, a recent panel on food and sustainability discussed similar challenges—*e.g.*, an auto-watering system might discourage presence in a garden (Hirsch, 2010). Others describe the potentially unproductive outcomes that technical interventions might have on community practices in the context of small-scale food production efforts (*e.g.*, Odom, 2009).

2.2.2 Tools for community sensing and scaffolding

With these critiques as a backdrop, participatory sensing platforms are increasingly being designed to support collective engagement with local issues and foster dialogues within and across communities. For instance, some HCI systems support sharing and discourse around collected data: the Common Sense project invites communities to annotate digital measurements with personal narratives (Willet et al. 2010), while inAir allows friends to view air pollution levels in each other's households (Kim, 2010). More broadly, urban sensing has been discussed as showing a paradigm shift from purely engineering and scientific fields, and towards pervasive technologies that span political computing, aesthetics, and participatory design (Cuff et al. 2008). For instance, sensors are being discussed in the context of 'participatory urbanism'—as tools that raise public awareness of and participation in environmental issues (Paulos, et. al, 2008).

Additionally tools have been developed to support scaffolding and sharing between individuals with various degrees of expertise, such as a digital augmentation of outdoor environments to facilitate learning (Rogers et al., 2004), or mobile phone applications to encourage outdoor observations (Ryokai et al., 2011). These research projects extend participatory sensing beyond personal awareness and behavior change and towards co-production of knowledge between professional scientists and citizen communities.

In summary, this section discussed how citizen science initiatives aggregate local information—in the form of observations, narratives, experiences, and sensor data—along with professional research and analysis to co-produce knowledge and expertise. I have presented an overview of related HCI work, which focuses predominantly on participatory sensing platforms for collecting and sharing local data. I have also noted a recent trend in HCI literature to critique purely techno-centric solutions, and pointed to a few projects that focus on scaffolding and community sensing. I examine the practices of local knowledge gathering in more depth in Chapter 5, which reports on the practices of "reading" biomarkers—living systems that reveal information about the environment.

2.3 Making hybrid systems

How is local knowledge contextualized, interpreted, and communicated? The information collected by West Harlem residents, for instance, was assembled into risk maps—physical representations of residents' self reports along with data from scientific instruments, and the area's geographic and urban features. These maps were not merely showing scientific data—they revealed entanglements between respiratory illnesses and the installment of an environmentally hazardous plant in an economically and racially marginalized neighborhood, the government's inability to adequately address the situation, and the efforts of scientists and residents to make sense of and improve these circumstances.

Latour discusses *things* as physical instantiations that "no longer have the clarity, transparency, obviousness of matters-of-fact" (2005). These things, not unlike Heidegger's gatherings of elements, materialize heterogeneous ideas and relationships between human and non-human actors. Things are thus comprised of hybrid materials and methods. They are constantly changing and being changed by people and circumstances.

2.3.1 Hybridity in design

The design of systems as active, heterogeneous things has been widely discussed in recent literature, most notably in *Design Things* by Binder et al. (2012). The authors differentiate between a designed device, which serves to fulfill a particular function and a designed thing, which modifies space and produces new knowledge beyond its function. Simply put, a designed thing is capable of "opening to its users new possibilities of action and interaction" (*ibid*). DiSalvo *et al.*, (2014) argue for importing these ideas into HCI's political computing research. The authors show, through a set of case studies, how making things can serve as approach for engaging with matters of concern and creating publics. In this way, things operate across seams—boundaries between domains, ideas, and stakeholders.

Boundaries and seams

This recognized value of hybridity is closely associated with Chalmers', *et. al*. ideas surrounding seamfulness (2004) and the discussions of categories and boundaries from Bowker and Star (1999). Both perspectives talk of seams or boundaries as generative, not things to be necessarily covered up, but junctures that lend themselves to new ways of seeing. For instance, Chalmers, *et. al.* celebrate "undesired seams" in a network topology as a rich design space. Swan et al. similarly identify those spaces where things fall between and betwixt as ones that allow for conventions to be disrupted and alternative ways of ordering and knowing to be produced (2008).

Material Beliefs, a multidisciplinary project at Goldsmiths University, can serve as a specific example of work aligned with these ideas (Beaver et al., 2009). Prototypes arising out of this research are, arguably, created not with the aim of achieving a specific scientific outcome, but rather as a way of materializing complex relationships between the human body, technology, and science. In his analysis of Material Beliefs, Michael (2011) illustrates that a designerly approach to public engagement with science is less concerned with solving particular problems and more focused on eventuation—how material and human actors can be gathered to support inventive, sometimes playful problem making (*ibid*). For instance, one prototype to arise out of this research is the *Neurospcope*, a system that enables users to observe and interact with (send electrical signals to) a culture of brain cells that is housed in a remote laboratory (Beaver et al., 2009). This artifact affords interactions that touch on the strange and familiar: the prototype is brought close to the viewer's eye, not unlike looking through a microscope, albeit the its shape resembles something that might be found in a futuristic kitchen. The Neuroscope thus sits at the seam of scientific and ordinary, living and non-living, intimate and remote.

In the remainder of this section, I want to give thought to the physical methods and platforms that enable making. Specifically, I focus on recent developments in DIY (Do It Yourself) platforms, practices, and cultures. In doing so, I hope to show how the DIY movement has influenced and co-evolved with making practices in and out of academic settings.

2.3.2 DIY cultures and practices

DIY can be defined as any creation, modification or repair of objects without the aid of paid professionals. DIY practice predates recorded history as human survival itself often relied on the ability to repair and repurpose tools and materials. Over the past few decades, new affordable materials and sharing technologies facilitated the rise of DIY as cultural and social practice. One of the earliest "modern era" DIY communities formed among amateur radio hobbyists in the 1920's. These hobbyists relied on amateur handbooks, which stressed "imagination and an open mind" nearly as much as the technical aspects of radio communication (Haring, 2008). Ham radio enthusiasts often met in person to discuss their work as well as unrelated social subjects. They continued to thrive rebelliously during World War II, when a ban was placed on amateur radio communication. Rebellious attitudes continued to pervade pirate radio stations of the 1960's and handmade 'zines' expressing the punk aesthetic in the 1970s' (Wright, 1998).

Later in the 1980's, low-cost MIDI equipment enabled people without formal training to record electronic music, evolving into the rave culture of the 1990's (McKay, 1998). During this time, computer hobbyists also formed communities to create, explore and exploit software systems, resulting in the Hacker culture. Today's DIY cultures reflect the anti-consumerism, rebelliousness, and creativity of earlier DIY initiatives, supporting the ideology that people can create rather than buy the things they want. These movements have influenced and at times co-evolved with industry and academic practices, as in, for instance, the development of the Apple computer within the Homebrew Computer Club.

DIY communities

Recent breakthroughs in technology allow people to quickly document and showcase their DIY projects to a large audience. New tools also allow enthusiasts to collaboratively critique, brainstorm and troubleshoot their work, often in real-time. This accessibility and decentralization has enabled large communities to form around the transfer of DIY information, attracting individuals who are curious, passionate and/or heavily involved in DIY work.

Thousands of DIY communities exist today, varying in size, organization and project structure. For instance, Instructables[9] allows members to contribute asynchronously on a variety of topics, while Craftster[10] and Ravelry[11] focus on specific projects such as knitting, crocheting or hip craft. Some communities, such as Dorkbot[12], revolve around smaller in-person gatherings and some, such as Etsy[13] enable hobbyists to trade or sell their projects. These communities and their underlying practices have been of great interest to HCI.

An early workshop held at CHI'09 initiated an early dialog between the HCI and DIY practitioners (Buechley et al., 2009). This popular gathering explored the methods, values, and materials of the DIY movement. The workshop covered themes such as open source hardware and software, sustainable design and reuse, and the political implications of DIY, to name a few. Over the past few years, workshops have continued to coalesce academic research with various strands of DIY. For instance, Kaye et al. (2011) examined cross-cultural perspectives on leisurely tinkering, hacking and crafting at a workshop at CSCW'11. Other workshops have focused on specific types of DIY activities such as bookbinding (Rosner et al. 2010) or digital fabrication (Mellis et al., 2013).

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[9] Instructables. http://www.instructables.com, accessed 2013.
[10] Craftster. http://www.craftster.org/, accessed 2013.
[11] Ravelry. https://www.ravelry.com/, accessed 2013.
[12] Dorkbot. http://dorkbot.org/, accessed 2013.
[13] Etsy. http://www.etsy.com/, accessed 2013.

In addition, a range of field studies and qualitative research provides insights into existing DIY practices. For instance, Torrey *et al.* (2007) explore information seeking among crafters, while O'Connor's ethnographic study (2005) focuses on glassblowing; Rosner et al. (2009) uncover IKEA hacking practices, and Torrey *et al.* (2009) focus on How-To documentation among hobbyists. This research, along with my own survey of DIY communities (Kuznetsov et al., 2010) reveals a unique set of values: open sharing, learning, and creativity over profit and social capital. Also of note is that DIY communities embrace expertise sharing by professionals and amateurs alike, which serves is a radical departure from more traditional models where knowledge is dissipated by a few experts, while the majority of users merely adapt this information to their needs (Trigg et al., 1994).

Hybrid tools and platforms

As part of DIY practice, artifacts are created, modified, and refurbished. A heterogenous set of materials is drawn upon, along with knowledge across domains, skillsets, and levels of expertise. For instance, an early study by Hartman et al., (2006) focuses on "mashing", the practice of reconfiguring system elements as a design activity and "mash-ups" as new types of design artifacts. Platforms that enable this sort of fast, hybrid making have been the focus of many HCI initiatives. Examples include Sketching in Hardware—a creative workshop for physical prototyping; Simple Haptics—a suite of tools for creating haptic interfaces; electronic popables to support paper computing (Holmquist, 2006); or numerous e-textile workshops with the LilyPad as a ubiquitous tool for education (*e.g.*, Buechley and Eisenberg, 2008, 2009). Buechley *et al.* (2009) integrate hardware electronics into textiles to make e-textile technology available to non-experts. Similarly, Mellis et al., integrate DIY electronics with a suite of customizable hardware and form-giving tools.

New tools and platforms are thus co-evolving with a vibrant DIY culture. The heterogeneous DIY assemblies—sharing mechanisms, prototyping tools, and analog and digital materials, embody diverse skills, interests, and concerns in the form of physical artifacts. The hybrid and evolving nature of these artifacts aligns them with *design things*: they are never seen as finished projects, but rather, as modifiable and customizable concepts shaping and being shaped by DIY communities. The increasing accessibility of DIY practice paves the way for making, reconfiguring, and appropriating systems for scientific inquiry, both in and out of academic settings. My dissertation builds on these ideas in Chapter 6 where I present hybrid systems that coalesce organic, digital, and analog elements to materialize environmental processes and community concerns.

2.4 Broader impact

Turning back now, for one final time, to the story that unfolded in West Harlem in the 1980's, it is worth reflecting on the impact of the transpired events. With the citizens and scientists thus expressing concerns, gathering knowledge, and making things, the outcome was this: a tightening of EPA air quality standards and a 1.1 million dollar settlement with the City for the damages incurred from the operation of the sewage treatment plant. Changes in public policy and the city's compensation for biological damage to residents exemplify the types of impact that can transpire from citizen science initiatives. In this section, I focus on the latter, which highlights the increasing role of biology and value as a point of negotiation within and across science communities.

The settlement between WE ACT and the city assigns monetary value to the harm inflicted on the residents' biological bodies—shortness of breath, onsets of asthma attacks, watery eyes *etc*. The concept of *biological citizenship* was first discussed by Petryna (2002) in her account of the Chernobyl Nuclear Power Plant workers who demanded compensation for the damages incurred during the 1986 disaster. In this context, biological citizenship is exercised through claim to welfare based on biological damages. Through a negotiation between citizens, governments, scientists and doctors, economic value is quite literally being assigned to biological well-being. Rose et al. (2007) unpack this emerging concept of *biovalue* as 1) the costs and benefits of safeguarding citizen populations; 2) the economic value of manipulating aspects of human healthcare—*e.g.*, patents, organ banks, etc.; and 3) the ethical value in biotech innovations.

Of course, biology and biovalue has, in some ways, always been intertwined with ideas of citizenship: from the pragmatic association with where one is born, to the more contentious questions of national identity being shaped by race, economics, and family lines. Globalization is arguably blurring geographic boundaries by increasing connectivity between cultures, economies, and community practices (Rose et al., 2005). These developments are bringing the concept of citizenship as a purely national concept into question (*ibid*). Recent breakthroughs in biology and genetics are radically changing people's understanding of personal, family, and cultural identity, as well as the types of agency they can exercise as biological citizens. Among the most significant contributing factors is the shift from biology being treated as a natural science and towards domains within biology—*e.g.*, computational biology and synthetic biology—being framed as engineering fields.

2.4.1 Biology as technology

Biology, the study of living organisms, has a long history of shaping and being shaped by technology. From early advancements in microscopy, to the more recent sequencing of the human genome, biologists are becoming increasingly reliant on digital tools that support routine work practices. More recently, the power of modern computational platforms has been enabling the modeling of complex biological systems in *silico*, often replacing aspects of wet-lab experimentation altogether (Carlson, 2010). The past decade also marks the recognition of synthetic biology as its own field, aimed at exploring "the design and construction of new biological parts, devices, and systems" and "the re-design of existing, natural biological systems for useful purposes"[14]. This vision to construct and manipulate living systems is not a futuristic speculation: the treatment of biological elements as engineered building blocks has already led to a range of new biological organisms being synthesized. For instance, 2010 saw the implementation of the first cell controlled by a synthetic genome (Gibson et al. 2010), not to mention the growing number of genetically modified vegetables now widely available as consumer products.

With the goals of engineering biological systems being clearly articulated and in many cases already achieved, biology is adopting a host of other technoscientific terms and values. These range from the actual practices of bioengineering, such as the adoption of the 'BioBricks standard'—modular DNA sequences that can be "assembled" into biological "circuits" (Knight et al., 2008), to the more startling cases where the concepts of optimization, efficiency, and standardization are being applied to living systems. Moreover, the manipulation of biological function is not confined to plants and animals, and is often extended to human beings as in, for instance, the domains of stem cell research or genetic therapy. As Rabinow (2008) argues, even the Human Genome Project itself, an effort to map the base pair sequences of the human DNA, conflates biological knowledge with biological power. As Rabinow points out, "the object to be known—the human genome—will be known in such a way that it can be changed" (*ibid*, 182).

New concerns

Not surprisingly, these advancements in biotechnology are giving rise a host of new concerns. On one hand, biology is being discussed as one of the most promising areas of our time (Bennet et al., 2009). It has been speculated to answer some of our greatest challenges—the global food and water crisis, synthesizing bio-fuels, and supporting longevity and human health. At the same time, concerns are regularly voiced about biosafety (*e.g.*, the consequences of releasing invasive genetically modified species into the environment, or producing organisms that behave outside of our control), as well as the ethics of "tampering with nature" and operating at the intersection of life and non-life (Ledford, 2010; Schmidt, 2008). Moreover, questions as to who is doing the science, to what ends, and how it is legitimized in and outside of laboratories are increasingly debated.

[14] Synthetic Biology. http://syntheticbiology.org/ Accessed June 2014.

2.4.2 Biological citizen publics

With the engineering-oriented framing of biology, the blurring of national boundaries through communication tools and global economies, and the new types of concerns being raised, ideas about citizenship, and indeed biological citizenship, are transforming in several ways. Most notably, citizenship as an identity defined by a particular geographic region is being brought into question. This is due, in part, to new genetic testing services that reveal ancestry ties across continents and migrations of people between countries. At the same time, biovalue is being negotiated and transferred between citizens, governments, and scientists on an unprecedented scale, and often in surprising areas of human life. For example, new practices are arising around objects of biovalue, including the patenting of cell lines, and the establishment of sperm and tissue "banks", as well as "gift economies" whereby donations of biological matter such as blood or organs is resulting in social ties between individuals and communities (Rabinow, 2008). Within this new political economy of hope (Rose et al., 2005), biology is increasingly lending itself to participation from outside of professional settings. New initiatives—from health advocacy groups to biology hobbyist communities—are arising to interpret, contest, and construct biological knowledge and value.

Do It Yourself biology

The conflation of biology and computation is inspiring other phenomena associated with engineering fields, namely the rise of the open source movement and its emerging publics. Over the past decade, DIYbio (Do It Yourself Biology) has coalesced as a growing community of professionals and hobbyists who pursue biology outside of academic and institutional settings. Adopting the language of computation and the practices of other DIY movements and hackspaces, 'garage biology' focuses on open-sourcing and tinkering with biology. DIYbio.org, a forum and network, which lies at the core of this community, emphasizes "making biology an accessible pursuit for citizen scientists, amateur biologists, and do-it-yourself biological engineers who value openness and safety"[15].

DIYbio initiatives worldwide range from independent bioartists[16] to meet-ups of hobbyists and professionals, biotech non-profits and fully-functional grassroots laboratories. Their work covers a spectrum of art, science and engineering, including DNA extraction, embedding bacteria in textiles, mapping genetic traits, developing biosensors, or replicating professional lab equipment with off-the-shelf parts, to name a few. As a public, the DIYbio community has been described as emerging *in situ* with the science itself (Mackenzie, 2009). That is, DIYbio is

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[15] Diybio. Diobio.org

[16] Some examples include the work of Turr Van Balen (http://www.tuurvanbalen.com/) and Anna Dumitriu (http://web.mac.com/annadumitriu)

concerned with science practice and not merely its outcomes. In an effort to change how science is *done*, DIYbio publics operate by reconfiguring science practices: making, experimenting, and tinkering with biology protocols, systems, and tools outside of professional settings.

Public participation in genetics

In addition to these bottom-up DIYbio initiatives, the availability of large-scale professional genetic testing services is giving rise to different types of concerns, connections, and activism. Affordable genetic sequencing tools coupled with more intuitive visualizations of the results[17] are increasingly turning personal DNA into an object an inquiry. For instance, services such as 23andMe allow participants to view their genetic health and ancestry information, including traits (*e.g.*, ability to taste bitter flavors), risks (*e.g.*, Alzheimer's disease), and ethnic composition. This type of information serves as both an individuating and a collectivizing force. On one hand, genetic makeup is revealing unique features of individuals, sometimes construed in terms of social categories (*e.g.*, normal/abnormal); at the same time, communities are emerging around shared genes or genetic conditions.

Thus, while the DNA testing itself is done in professional laboratories, meaning making often occurs "from below"—though the sharing of experiences, narratives, and intuitions about genetic traits, as well as collective debates and interpretations of scientific research. Moreover, *biosociality*—the coalescing of people around shared biological characteristics—is giving rise to new forms of agency (Rabinow, 2008; Neuhauser, 2009). For instance, groups formed around genetic diseases (*e.g.*, Huntington's disease) are actively influencing the relevant scientific research, both by contributing their own tissue samples and medical data to research initiatives, as well as by shaping the research itself through advocacy, funding, and public awareness campaigns (*ibid*). Not unlike the other citizen science examples I discussed earlier, these efforts pluralize and collectively construct science knowledge.

2.4.3 Relevance to HCI

There are many reasons for focusing on biology and genetics within HCI. First and foremost, claims to biological citizenship are increasingly predicated on people's ability to understand science. Yet, studies of public understanding of genetics show limited, sometimes problematic accounts. This is often due to mixed cultural messages perceived through television shows and science fiction movies, as well as pre-existing mental models of genetic tests, diseases, and kinship (Bates et al., 2010; Michie et al., 2003; Lanie et al., 2004; and others). Scientific and

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[17] Examples include the Genographic Project DNA Ancestry Kit (nationalgeographic.com); ancestryDNA (dna.ancestry.com); or 23andMe (www.23andme.com)

technological literacy has been a major focus within HCI, from learning and scaffolding tools for non-experts (*e.g.*, Rogers et al., 2004; Clegg, 2010; Willet et al., 2010) to HCI techniques being applied to collecting and sharing biological data (*e.g.*, Shaer et al., 2010). In addition, emerging systems for visualizing genetic data resonate with HCI' literature on personal informatics (*e.g.*, Li et al., 2010), albeit the information shown is rooted in personal DNA, rather than behavior patterns collected over time.

More broadly, as biology—both in and out of professional labs—continues to operate at the intersection of human and machine, organic and synthetic, and lay and professional, HCI is presented with a host of challenges and opportunities. At the very least, the emerging intersections across biology and computation reignite longstanding debates on the nature of machines and humans' interactions with them (Suchman, 2007; Winograd, 1991). The less explored design space around the treatment of living systems as engineering constructs and the ethics of manipulating biology also resonates with HCI's value-driven approaches and reflective technologies (*e.g.*, Hallnäs et al., 2001; Friedman et al., 2006; Sengers et al., 2006; and many others). Moreover, tools that enable communities to act around shared biological concerns are reminiscent of politically-oriented approaches to link people through their actions (Dourish, 2010).

This section thus outlined some of the emerging trends in biology, and the discourse framing it as an engineering field. Specifically, I described how the intersections between biology and computation are giving rise to publics of biological citizens who aim to transform science practice within and outside of professional settings. These developments are resulting in new technologies, science knowledge, and biovalue. With all this as a backdrop, I explore public participation in biology and genetics through fieldwork with DIYbio and 23andMe communities, and the physical prototyping of bio-electronic artifacts in the last two chapters of my dissertation.

2.5 Summary

I began this chapter by presenting the story that unfolded in West Harlem in the 1980's, from the installment of a sewer treatment plant and the assembly of WE ACT, to the outcomes of lay-professional collaborations, which had broader consequences for public policy. Through the lens of these events, I have examined some of the practices and underlying technologies that bring citizen science publics into being and enable them to act towards changing the status quo. Specifically, I described how communities form around shared matters of concern, how practitioners with different degrees of expertise gather and co-produce local and professional knowledge, how hybrid things are created to materialize heterogeneous information and issues, and finally how value is negotiated and attributed to biological well-being, resulting in broader impact on science practice. I have tried to address these processes through the perspective of HCI and design, focusing specifically on tools and methods for expressing concerns; sensing systems for gathering knowledge; DIY and professional methods for making hybrid systems; and finally, design opportunities that arise at the intersection of biology, technology, and public participation.

It is important to note that the processes outlined here—expressing concerns, gathering knowledge, making things, and creating broader impact—do not occur linearly. Rather, these are highly iterative and recursive practices that can be broadly associated with aspects of post-normal science (Funtowicz et al., 1991). In short, post-normal science refers to the issue-driven study of complex systems. Such systems often embody opposing values, incalculable factors, and irreversible consequences. Rather than trying to reduce these into quantifiable "facts", successful inquiries support plurality of legitimate opinions, broader dialogue, and a deeper understanding of the situation. This approach reflects the multi-faceted dimensions of science initiatives in the real world. The complexity of such efforts is perhaps best illustrated by none other than West Harlem residents' description of WE ACT on their website:

> WE ACT for Environmental Justice was founded and incorporated in 1988 as the result of local community struggles around environmental threats and resulting health disparities created by institutionalized racism and the lack of social and political capital…[18]

Environmental science, human health, eco-racism, and income inequality are all intertwined in the above. As I hope to show in the remainder of my dissertation, these and many other types of entanglements shape the motivations, practices, materials, and outcomes of citizen science publics.

[18] http://www.weact.org/Home/WEACTHistory/tabid/180/Default.aspx

3 Place-based community sensing

With participatory sensing being the primary HCI approach for studying citizen science, I begin by asking how citizen-collected data can become a point of reflection, a tool for taking action, and a matter of public concern. To explore this question, I challenge the conventional notion of sensors as passive instruments of data collection. The act of placing a sensor, particularly one with politically or environmentally loaded content such as air quality, can be an overt and public act. The mere presence of such a sensor can project a statement or concern about a place, and the resulting sensor data can be broadcast within and across communities to provoke and transform perceptions, usage, and labeling of space.

This chapter thus re-envisions low-cost sensors not only as instruments of data collection, visualization and sharing, but also as an approach for authoring, engaging and provoking a wide range of public spaces by the individuals who occupy them[19]. I propose a system of modular, low-cost, networked sensors that measure environmental factors such as air pollution, radiation, water quality, and noise, among others. Rather than belonging to a particular person or space, these sensors are designed to invite stakeholders—people occupying or passing through a space—to move and leave sensors in locations of interest, thereby exploring and engaging with their environment.

I explore this approach by first deploying sensor probes (non-functional 'mock' sensors) amongst four communities for parents, students, bicyclists and homeless. Building on findings from this study, I then present a system of networked movable sensors that monitor air quality and weather parameters and report this data to a central website in real time. I report on the deployment of this functional system with four urban communities. I draw on both studies to suggest design implications for sensing systems as a vehicle for expressing matters of concern.

[19] Sections of this chapter were previously published (Kuznetsov et al., 2011; Kuznetsov and Paulos, 2010).

3.1 Activating urban spaces with sensor probes

Drawing on past probe literature (*e.g.*, Mattelmäki et al., 2002; Iversen et al., 2003), I present users' engagement with hypothetical prototypes to investigate questions such as 1) how do communities of stakeholders perceive issues of authorship, anonymity and engagement in public spaces; 2) which spaces afford curiosity about specific environmental factors across different communities; and 3) how participatory sensing be leveraged as a platform for city-wide grassroots activism. The use of probes (vs. specific working sensors) enables us to adopt Boehner et al.'s (2007) open dialogical approach: the work responds to rather than ascertains facts about participants' experiences. Instead of moving towards a single and correct understanding of an ultimate sensing system, study findings open broader interpretations and design trajectories in this area. Moreover, this method enables us to quickly acquire knowledge and envision place-based sensing without the initial overhead and cost of developing functional devices.

3.1.1 Environmental sensor probes

The study was scoped around six factors, which participants agreed covered most of their concerns: exhaust (vehicle-related pollution), smog (industrial pollution), pathogens (bacteria, germs, etc), noise, chemicals (cleaning products, pesticides, VOC's, etc.) and dust. I developed probe kits, each consisting of six mock environmental sensors (1" acrylic cubes) with an acrylic half-sphere on top to simulate sensor input (Fig. 3.1). Magnets along the bottom of each probe enable easy attachment to metal, non-horizontal surfaces.

3.1.2 Study design

To gain insight into how stakeholders spanning diverse age groups, interests, urban spaces, social and economic backgrounds approach sensing and public authorship, the study focused on four communities, making the following assumptions about each:

- Students are a young demographic occupying spaces in and around universities, with interests that reflect similar educational backgrounds and

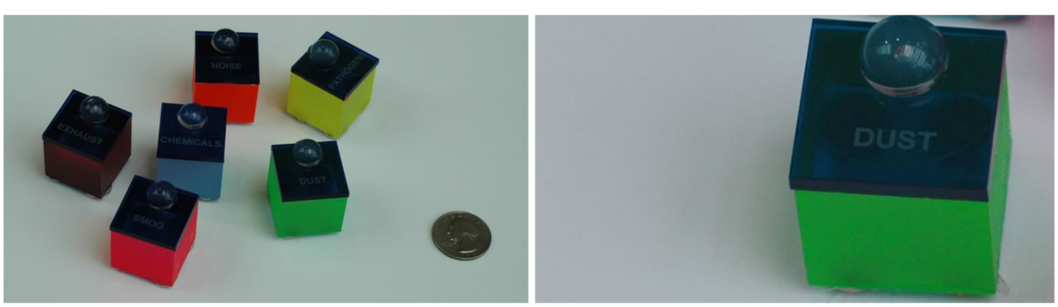

Figure 3.1. All six sensor probes (left) and dust probe (right).

lifestyles

- Parents form an older group, expressing personal and family interests in spaces that revolve around children (schools, playgrounds, etc) as well as work (office, etc.) and friends (theatres, malls, etc)
- Bicyclists traverse a wide range of urban spaces with vested interests in roads, parks and traffic, among others
- The homeless are a low-income, nomadic community, with socio-political perspectives that lead to unique appropriations of technology, often overlooked by mainstream HCI literature (Le Dantec et al. 2008)

The study recruited 15 participants: 4 students, 3 parents, and 3 cyclists from local mailing lists and forums; and 5 homeless through a local shelter. Participants first completed an informal pre-study interview about their perceptions of the city, prior expressions and contributions to public spaces, and environmental concerns. We then provided each participant with a probe kit, explaining the types of measurements that were simulated by each probe (*e.g.*, "This is a mock pathogen sensor, it represents the measurement of bacteria or germ levels"). Participants were asked to use the probes as if they were real sensors over the course of one week, taking measurements, placing or leaving them throughout public locations during their daily routines.

Participants photographed sensor placements with cellphones, personal cameras, or disposable cameras that we provided. Participants then returned for an informal wrap-up interview discussing their experiences over the week. Compensation included $10 for the initial interview and another $25 for completing the entire week-long study. We encouraged participants to leave the probes for longer periods of time, emphasizing that we do not need to collect them. We did not suggest a minimum number of placements or photographs, suggesting that participants do 'what feels natural' as if these sensors were real.

3.1.3 Findings

Participants tended to carry all probes throughout the study. Everyone commented on the attention attracted by publically placing the probes and expressed different comfort levels for doing so (discussed below). Despite wanting to monitor spaces for long periods of time, no one actually left the probes

Figure 3.2. Parent sensor placements: pathogens probe on shopping cart; dust probe in school gym; exhaust probe at school bus parking lot.

unattended, primarily because participants did not want to return for the probes in order to place them somewhere else, as well as to avoid theft or loss. Below, I highlight key findings, centered around *i)* common sensor placements, *ii)* how participants wanted to visualize the data, and *iii)* their willingness to share and act on this information.

Sensor usage and placement

Not surprisingly, some sensor probes inspired similar placements across all four groups. For instance, participants from all four communities wanted to monitor exhaust and noise levels at bus stops and street intersections, pathogens in bathrooms, dust, noise and exhaust levels at construction sites, and chemicals near sewers, hospitals, gas stations and water sources. While parents, homeless and students wanted to monitor pollutants continuously in specific locations, cyclists wanted carry and use the sensors while biking. As P5, a cyclist, explained: "*I don't always hang out and stop because I'm just passing through*".

Parent participants tended to involve their kids in the study (*e.g.*, "*It was fun to actually find the places… my kids were totally involved*", P9). Not surprisingly, parents' placements were motivated by their children's health (Fig. 3.2). They were most interested in the pathogens sensor, wanting to monitor germs in bathrooms, theatre seats, school gym, clothing store, stair railings, trashcan, and shopping cart. In addition, the pathogen probe was coupled with the dust probe in a recreation center, subway, doctor's office, and library. The exhaust probe was also common: near playground ("*constant pollution is coming out, black smoke from the buses… if kids are in this playground during the summer, then they're breathing in all of that*", P10), at a school bus stop ("*they're [kids] all sitting there in the morning and waiting for the bus*", P9), and by a subway stop.

Similar to the parents, homeless participants also frequently used the pathogen sensor, but their placements were motivated by public health concerns rather than family health. They placed probes in public bathrooms (at CVS, McDonald's, Hilton Hotel) because "*there's like a lot of people there and there's restaurants there too*" (P12), in a bus because "*a lot of people sayin they're getting sick this week so I'm wondering—cause people are on the bus a lot together*" (P13), in the homeless shelter dorm, on children's toys at a doctor's office, door handles, and floor of common area in the shelter. Homeless participants also placed combinations of exhaust, smog and

Figure 3.3. Homeless sensor placements: dust probe near construction site downtown; chemicals probe at fast food restaurant; exhaust probe at bus stop.

dust probes throughout bus stops ("*I picked the bus stop cause lots of people are always there*", P12) near cars, and on street poles and fences, focusing on construction sites and heavy traffic streets (Fig. 3.3).

Cyclists and students focused on locations that were of interest to their particular community. For instance, P5, a cyclist, simulated placing sensors that were of concern to other riders (Fig. 3.4): noise and exhaust sensors in parks, on bike trails ("*because people use this to commute in and out of the city so it gets a lot more traffic and exhaust from that and the noise as well*"), at a library and food co-op ("*lots of people hang out there*") and by 'the wall'—a meeting place for bike events. Likewise, students picked locations that were visited by other students (Fig. 3.5): dust and pathogens in a library ("*people sit in the library for hours and hours—they get exposed to dust and pathogens*", P2); exhaust, noise, and/or dust sensors near bus stops or intersections, since "*there are a lot of people passing by*", P1).

Students and cyclists were also interested in the correlations between different pollutants. For instance, cyclists wanted to measure all factors simultaneously to identify causes of pollution:

> I was more curious about how these different pollutants work together… I would take a few off and look for correlations between them to kinda figure out what some of the causes are… like on Butler street there's a lot of 18wheelers that go around so if there was a way to redirect them and there'd be less noise and exhaust but would there also be less pathogens and less chemicals? (P6, cyclist)

Likewise students wanted to monitor chemicals and pathogens in sewers across neighborhoods ("*low income vs. high income to see what's the difference*", P1); or compare exhaust and smog levels in parks vs. street intersections ("*difference between a place that is green and the city center*", P2).

Authorship and Expression

Of the four communities, students and cyclists most strongly expressed feeling awkward during sensor placement, but became comfortable in time:

> It's kind of awkward because when I'm trying to put it there, everyone was watching, 'she's crazy or something' it was kind of awkward but then you get used to that. (P1, student)

Parents were less self-conscious about sensor placement ("*I didn't care I thought it was pretty interesting*", P9). Homeless were most comfortable with the study, as P12 explained: "*people looked at me funny I didn't feel awkward though. I just said I was doing a*

Figure 3.4. Cyclist sensor placements: exhaust and dust probes at a bike lane; all sensor probes attached to bike; exhaust, dust and chemical probes in public park.

study". One homeless participant, P11, even involved his friends in the study who appeared in numerous pictures ("*I asked friends to hold the thing* [probe] *up*", P11).

Students and homeless wanted sensors to be more visible, especially when left in public spaces.

> It's good to be noticeable. It's nice to have different colors. It's a way to increase awareness of this topic. (P1, student)

> If they [sensors] blink yea that would be good… if they blinked like even if they were on just to let you know they were on they were blinking (P10, homeless)

Both students and homeless also suggested posting 'notes' or 'signs' to indicate when pollution levels were too high. For instance, P1 explained that each sensor "*should be bigger or it has have a sign saying 'we're measuring …' and what these levels are*".

Conversely, cyclists preferred less visibility for the sensors:

> I don't want people thinking that these are some sort of weird dangerous things. If they were very unobtrusive then I'd be more likely to [put them up]… or if I could make it look like it belonged there. (P7)

Feedback from parents revealed a third perspective on sensor appearance: a tension between visibility and secure placement. On one hand, parents wanted sensors to attract attention ("*I would like them a little bit brighter so they're more noticeable*", P10; "*I would've left it there, it brings attention to the city or to the company*", P9). At the same time, participants were worried that visibility may cause children or other people to "take it off", and a larger size would become unwieldy.

Participants from all communities wanted to represent data in terms of a benchmark ("*compared with the year before or something about the normal/standard levels*", P1) or abstractly:

> Green, red or some kind of indicator that says it's an acceptable level. (P3, student)

> Keep it simple, red, yellow green. (P10, parent)

> Flash red then text your phone. (P12, homeless)

In addition to displaying data on the sensors, participants suggested visualizations on phones of websites. Cyclists in particular preferred to view the data remotely, rather than "*looking at data* [on the sensors] *while trying to go somewhere*" (P6).

Figure 3.5. Student sensor placements: exhaust, chemicals and smog on park entrance sign; noise and exhaust at bus stop; dust and noise sensors in computer lab.

Data sharing and activism

Of all groups, homeless were most compelled to share sensor data with the general public, and especially with younger people "*it's really important to share with kids, I think*" (P12). However, they also agreed that their first response to harmful sensor readings would be to "*get outta there*" (P10) or "*move for sure*" (P11). Likewise, in many cases, parents saw sensor placement as a message in itself, for instance alerting stores to provide "*clean wipes near the [shopping cart] handle*" (P9) or "*to remind people if you can bring a q-tip with you maybe or wipes…. Use antibacterial before you start typing*" (P10, regarding dust and pathogen sensor near shared computer). However, parents did not see a need to publically broadcast this data unless it negatively impacted them:

> If it directly affected me or my children or them being in school… and I was presented with that information I would say yes we need to do something about this. (P9, parent)

Unlike the homeless group, the cyclist, parent, and student participants discussed sharing data within their specific communities. Parents, for instance, indicated that if they did discover unsafe sensor readings, they would first alert other parents through a school assembly, meeting or website, or a "*datasheet to give the parents in a parent packet*" (P9). Likewise, P5, a cyclist was enthusiastic about sharing data with his community "*If you're doing it from the cyclist perspective—people would welcome it. I'd feel like I'd be helping improve these spaces for my community*." Another cyclist suggested showing data to a mountain biking organization:

> One of the mountain biking organizations would want that data… if it turned out to be a real problem they'd want to collect it and present a point to the city or something. (P7, cyclist)

Several students said they would go as far as sharing data with local officials: "*give this information to the city center or council for them to take some action*", P1. However, P2 was also concerned with political implications:

> It's great to collect data but how would it be put to use? Would the city officials be seeing this? Could it be affecting their decisions? Would someone be in charge of this or would they have a panel go into city council to discuss how this can be changed? (P2, student)

On the contrary, homeless and parent participants were more skeptical of sharing data with authority figures. As P10, a parent, noted: "*I wouldn't have much faith in the city, it's not a priority*". Similarly, P11, a homeless participant, felt that "*there's nothing to do about it [sensor data]",* comparing the government to a "*whirling dervish*" that "*won't change anything*".

Lastly, some participants noted that the study itself raised their awareness. One parent said that "*it really did make me think about the environment*", (P9), specifically in the context of exhaust and bacteria ("*now I carry more antibacterial soap*", P10). Likewise, two homeless participants noted that the study heightened their sensitivity to environmental factors. P12 "*noticed a lotta dust and stuff*", while P12 was more watchful for germs: "*I gotta be careful put something in my hand open the door without touching it*".

3.1.4 Summary

The above section detailed the deployment of sensor probes to explore participatory place-based sensing across four urban communities. The findings reveal that the act of placing of physical sensors can be a point of reflection and engagement with space, suggesting environmental data as social currency within and across communities. By embodying unique community values, future sensing and visualization systems can serve to broadcast stakeholders' concerns, negotiate dialogues with policy makers, or bring communities together, thereby facilitating the creation of cohesive publics and serving as instruments of political, social, and spatial change. These implications are discussed in more detail at the end of the chapter.

3.2 Place-based air quality sensing

Drawing on findings from the sensor probes study, we developed a system of fully-functional place-based air quality sensors. Each sensor measures exhaust, dust or VOC's (volatile organic compounds), and the data is displayed on a community website (not the unit itself) to facilitate community rather than individual use of the system. Integrating commercially available sensors with off-the-shelf components, the exhaust sensors respond to gases emitted by vehicular traffic and diesel engines, VOC sensors detect compounds originating from paints, solvents or pesticides and dust sensors measure particulate matter (pollen, smoke, *etc.*). These factors are of serious public health concern within the geographic region of our study: our city was rated as one of the worst in the United States in terms of air quality and exposure to exhaust, dust or VOC's can lead to chronic respiratory illnesses, including asthma, bronchitis, inflammation or cancer. I describe the sensing system in detail below.

Figure 3.6. Functional place-based sensors: exhaust sensor attached to stop sign; dust, exhaust and VOC sensors attached to bridge.

3.2.1 System

We designed and built a system of networked air quality sensors entirely from off-the-shelf parts (Fig. 3.6). We intentionally chose low-cost and low-precision sensors to develop DIY (do it yourself) technology that can be re-created by non-experts without high-end calibration procedures. Our sensors provide relative rather than absolute (PPM, etc.) values, and the visualization enables comparison of VOC, and exhaust levels across different times and locations. Rather than focusing on scientifically precise values, our initial goal is to highlight variability across time and space.

Sensors

Our sensor circuit is supported by a custom PCB board that can be populated with exhaust, VOC, and/or dust sensors from Figaro (Fig. 3.7). In order to highlight specific air quality concerns and spatial affordance, every deployed unit was outfitted with a single sensor (exhaust, dust or VOC) and our participant groups received one of each. In addition, all units include a dual function temperature/humidity sensor and a light sensor. Input is processed by an Arduino-mini microcontroller, which interfaces with a Telit GSM/GPRS module to send time-referenced sensor data along with the unit's GPS coordinates as an SMS message. Units are powered by rechargeable 6600mAh lithium batteries.

The sensors enclosed in custom vacuu-formed polystyrene cases (4.0cm x 6.5cm x 13cm). Each sensor case is outfitted with a mounting magnet, hang strap, and carabineer, affording easy attachment to public surfaces. Units are branded with our university name and logo on the front, and contact information and sensor description on the back. Small holes in the case allow for air circulation and light inside the units, and although several deployments encountered significant rain, sensor functionality was not affected.

Maximizing battery life. The sensors function continuously for up to ten days by supporting three power modes: full power (300 mA) with sensors powered on and GPS/SMS transmitting, standard mode (40-100 mA) with sensors powered on and the GPS transmitter off, and low power mode (1 mA) with the system in

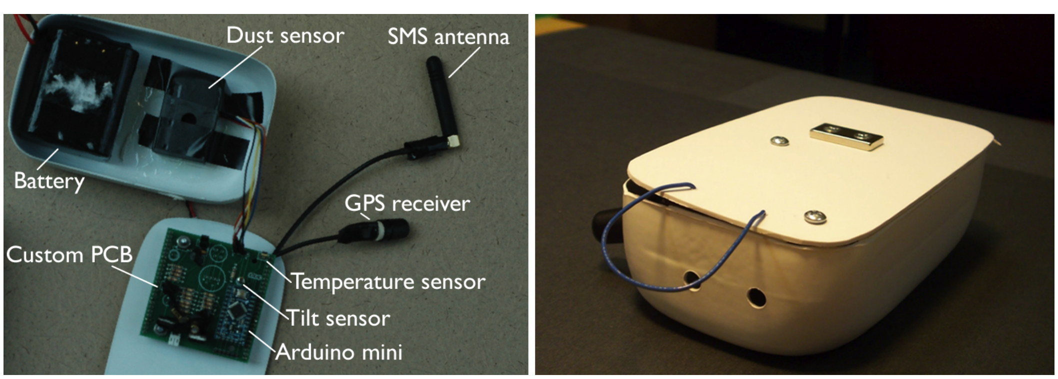

Figure 3.7. Dust sensor in case with parts labeled; back of case with magnet and strap.

sleep mode. During sleep mode, continuous sampling from a tilt sensor is processed to determine whether a unit is being physically moved (picked up, walked, biked or driven with). When movement is detected, units power up to full mode, transmitting GPS coordinates and sensor data every five minutes. However, if left static, units remain in sleep mode, changing to standard mode once every 30 minutes to sample sensor data and store it locally. The units then send the data in bulk every 5 hours.

Backend

Data from the units is sent as a comma-delimited SMS message to an e-mail address that is regularly polled by a script (cron-job). Since we did not calibrate the air quality sensors, all dust, exhaust and VOC values are scaled to a range between 1 (lowest) and 100 (highest) for consistency. Data is inserted into an SQL database, with separate tables for each of the studied communities. Consequently, participants can access sensor placements and data collected by their community.

Interface

Our front end, developed in php and javascript, leverages the Google Maps API and with Google Chart Tools to render data geographically (on a map) and temporally (through a series of interactive graphs).

Map. The map shows sensor placements as varied-size dots (sized according to air quality levels), connected chronologically with a line to illustrate the unit's path. Different sensors (dust, exhaust and VOC) are represented with different colors and can be toggled on and off, allowing users to track the units individually. Clicking or mousing over each location activates a tabbed info window. The default 'Overview' tab shows the latest data from the corresponding location: exhaust, dust or VOC value on a color-coded gauge along with temperature and humidity. Other tabs include temperature, humidity, air quality, and light data from the location as static line graphs. In addition, the map supports geo-referenced comments.

Graphs. The right side of the website contains interactive graphs showing data from all three sensors in the default 'Overview' tab, and from individual sensors along with temperature and humidity data under the 'VOC', 'exhaust', and 'dust' tabs. A draggable scale bar along the bottom allows zooming into parts of the graphs, and clicking on a point activates an info window over the corresponding location on the map. The 'Comments' tab contains a feed of all community comments, and clicking on a comment activates also the corresponding location.

3.2.2 Deployment

Sensor units (12 in total) were deployed with four urban communities of cyclists, parents, activists and homeless (22 participants, who were not from the previous study). As with the earlier probes study, these four groups were selected to capture feedback from participants spanning diverse age groups, interests, urban spaces, social and economic backgrounds.

Methods

Participants from each community completed a preliminary group interview exploring community concerns as well as activism, roles and attitudes in public spaces. Each group was asked to draw a community map showing locations they considered 'healthy', 'unhealthy', etc., on transparencies overlaying a map of the city, along with spaces where they would like to monitor and publically broadcast air quality. Participants were then presented with three air quality sensors (labeled dust, VOC, and exhaust) and introduced to the website with a walkthrough of basic features. All participants had access to a computer during the study, including the homeless who used a shared desktop that was donated to the shelter. Groups were instructed to move, place and leave the sensors throughout the city as they preferred, over the course of one week, photographing each location (with personal cameras or provided disposables). We encouraged participants to leave the sensors for longer periods of time, emphasizing that they were not expected to return them. We did not suggest a minimum number of placements or uses of the website, recommending that participants do 'what feels natural' for their group. After one week, participants returned for an informal wrap-up group interview discussing their experiences with our system. In addition, we observed participants' use of our website for 5-10 minutes to evaluate our interface. Each participant was compensated $10 for the initial interview and another $25 for completing the entire week-long study.

3.3.3 Findings

All sensors (except for 2, explained below) functioned as intended over the course of the study. Overall, participants enjoyed the project ("It was fun", parent), were impressed with our system ("this is awesome", homeless) and wished the study was longer ("I wish we had more time [to place sensors]", bicyclist). Most participants did not use the comment feature ("I didn't really notice it, plus I wouldn't know what to say", bicyclist). I now detail the findings, referencing data from participants in particular groups as: C, bicyclists; P, parents; H homeless; and A, activists.

Participants

We recruited four commuter bicyclists (1 female, age early 20's) through local bike forums. These cyclists are students who have been friends for several years, with two living together, and they see each other at least a few times a week. Participants voiced individual concerns ranging from bike hazards, to personal safety as affected by "*drug dealers, violence and vandalism*" (B3), and the homeless:

> There was a hobo sleeping our my porch once and… we also found recently… there's a building [across the street]- I think a hobo made it his home and it's just like a huge room with an old furnace and there's all this stuff of the hobo's. Yea, that's probably the biggest concern I have right now. (B2)

When asked to converge on a mutual concern, participants identified urban development, including the quality of streets, parks, and green-spaces, as well as economic and environmental disparities across the city. Participants agreed that street art was an effective approach for improving urban space ("*I think street art is like a way of art, and I see it personally as a way of doing that*", B2) and they have previously contributed to grassroots expressions including graffiti, guerrilla gardening, and murals to "*beautify the area*".

The parent participants (2 male, 1 female, ages 30's-50's) and their four children (1 female, elementary school ages) been friends for several years, meeting at neighborhood functions, children's play-dates and activities. Participants shared a host of concerns about urban infrastructure, from streets that are not bike-friendly to poor mass-transit. However, to resolve these issues, participants deferred to other groups such as bike advocacy organizations.

The homeless participants (five males, ages mid 40's-60's) were recruited through a local shelter. The shelter offers a shared dormitory, a common 'TV' area and shower facilities for a maximum of 60 days per person per year. Occupants range from people who temporarily lost housing, to individuals traveling through the state, or living in different shelters across the city over the past decade. Consequently, some of our participants are new to the shelter while others have known each other for years, and their routines vary greatly:

> When we leave here, everybody has some type of business to go to, to get up outta here, you know what I mean? To better their lives, and once all that is accomplished, then the park is... our meeting place, everyone comes through the park to get here. (H1)

The activist participants (4 male, 2 female, ages 20's-30's) recently moved to the city, but have known each other through an anarchist network, coordinating and meeting at various activist events over the past 3-4 years. Participants share a strong dislike for the police, as well as public spaces that do not afford gatherings (lack of open, accessible space). Broader issues fall under the umbrella of capitalism, oppression, and hierarchy ("*we actually do have a list that we've all agreed on*", P3).

> There's not so much action that you take against those really broad overview things. It's more like tackling really specific, often local issues that relate to those… focusing on realistic actual things that are affecting people's lives. (P5)

Sharing sensors

The four communities followed very different strategies for sharing and placing sensors. Bicyclists split up the sensors for the week such that everyone had access to one sensor, without particular preference for the type of sensor they used:

> [B4] lives all the way in south Oakland, and we live very close to each other so, we figured [B4] should definitely get one and then I took one, and these two live together, so they took one. (B3)

Parents, on the other hand, took turns using the sensors, each having all units for 2-3 days, and then handing them off to the next person ("*we divided 7 [days] by 3 [families]*", P1). The activist participants coordinated a set of placements for each sensor ahead of time, and took turns moving them to these locations within the group, based on individual routines and schedules. Lastly, although the homeless participants discussed specific locations (parks, street intersections, waterfront, etc.) to place the sensors, they did not coordinate a strategy for the study. Instead, individuals took whatever sensor was available as they left the shelter ("*whoever was up first got one, and I ended up with this one, I was the last one out the door*", H4).

Sensor placements

While several sensor placements were similar amongst all four communities (exhaust sensor at busy intersections), the groups' diverse sharing strategies coupled with the unique spaces they visited inspired different sensing behaviors (Fig. 3.8).

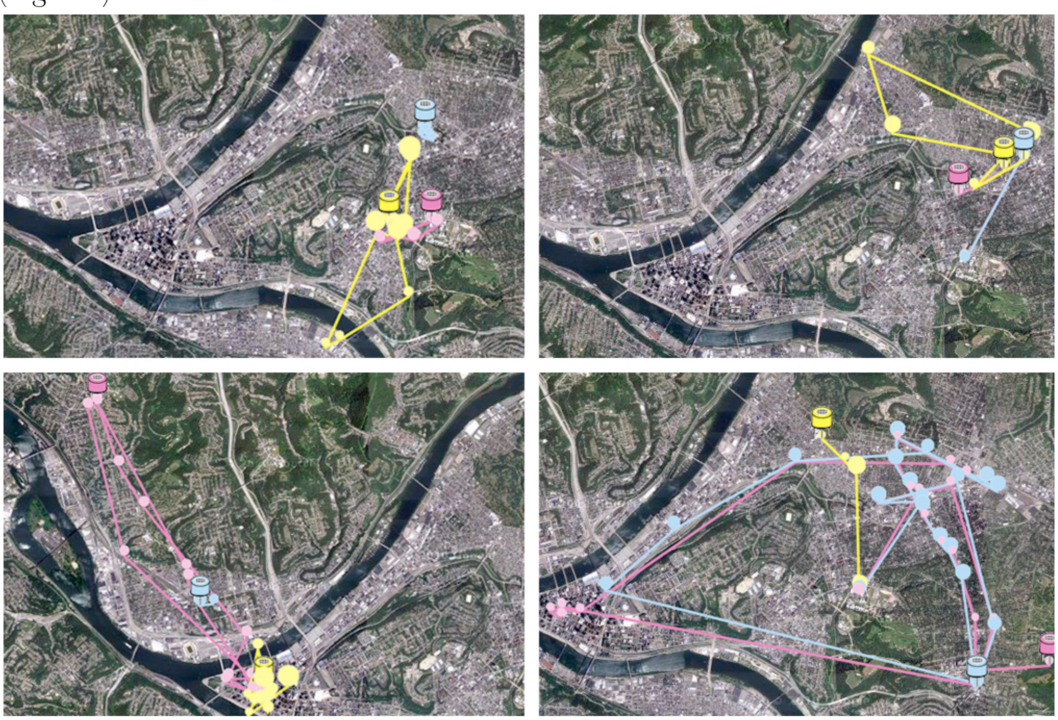

Figure 3.8. Sensor placements by bicyclists (top left), parents (top right), homeless (bottom left, and activists (bottom right)

Cyclists

Similar to cyclists in the earlier probes study, B2 carried the exhaust sensor with him throughout the study: "*I kinda just took it with me as I went on journeys, just to spread it around*". He placed it on a busy street near a thrift store ("*I thought it would be interesting to leave it for two days, just to get a dependence of time, if it goes up and down*", B2), post office, and park. B3 and B4 (roommates) shared the dust sensor, keeping it in their backyard for most of the week. B4 also left the dust sensor overnight on a bridge near a public library:

> You know the factory that's like right behind the library… yea so I wanted to know what that is, so I guess I was just curious if that would somehow affect the dust sensor in any way, so I kinda like pointed it towards that. And it's also right next to the park. (B4)

B1 did not attend the final interview but kept the VOC unit at what others identified as his friend's house on the map.

Parents

Also similar to parents' use of sensor probes, parents in this study involved their children in placing sensors. While parents tended to decide on locations, their children physically placed most sensors (on trees, street poles, etc.) and photographed the placements. P2 had the sensors first, using all three together to compare the measurements:

> First I put it in our yard, and then I thought, OK let's put it in a more public space, so I chose to put it in front of the Rite Aide [pharmacy near her house]. (P2)

An employee noticed the sensors and contacted the police, who in turn summoned the city bomb squad. Even though sensors were labeled with text detailing them as a locally approved research project, they were confiscated. Although the police were not initially sympathetic, we negotiated resuming the study and returned sensors to participants the same day, after several discussions with local authorities. During the interruption, batteries dislodged from the main board of two units (VOC, dust). However, participants continued to use the sensors, initially not realizing that two were broken. P3 and his children attached them to telephone poles using a ladder and nails:

> I wanted to basically be close to the river. We went further down and there were the factories and the robotics center, and the 43rd concrete center [factory]. There's also some foot traffic 'cause you can get to the river trail from there so there's a lot of dog walker. (P3)

P1 was interested in collecting more data ("*I was really going for the data, so I hung it in different places based on my interpretation of the study*", P1), placing the exhaust sensor at a street intersection and a bus stop; the dust sensor by his house and in a public park in a "meadow rife with pollen and plants"; and the VOC sensor in an alley, by a dumpster at a paint factory, with permission: "*we went inside [the paint factory] and we explained what it is we were gonna do.*"

Figure 3.9. Photographs of participant sensor placements: participant's daughter attaching VOC sensor to street pole; and exhaust sensor outside a children's hospital placed by activist; dust sensor attached to bridge by bicyclist.

Homeless

Since homeless participants did not have a specific plan for the study, H4 'ended up' with the VOC sensor, placing it in a tree in the park frequently visited by the homeless for the entire week:

> I didn't know if they ever spray for pesticides or if they have—any chemical agents on the grass- the fertilizers. (H4)

H3 and H5 shared the exhaust sensor, placing it at street intersections and bus stops throughout the downtown area.

> I put it on the main drag, like where all the bus traffic is… I thought it'd be a good spot 'cause usually when I'm standing, waiting for the bus, I could smell the exhaust fumes. (H5)

The dust sensor was taken by H1 along with the group's disposable camera. Our website shows this sensor moving extensively throughout the north side of the city, but its particular whereabouts remain unknown as H1 disappeared from the shelter and did not attend the final interview.

Activists

As part of coordinating community placements, P1 put the exhaust sensor in a tree in a park, and P3 and P5 retrieved it the following day, placing it on a street pole near a children's hospital. The VOC and dust sensors were initially at P2's house. The VOC sensor was then moved "*by a door in an alley, near the iron workers apprenticeship*" for a few days and then brought to an urban community farm collective ("*to see how much fertilizer and stuff is in the space where they grow food*", P6). The dust sensor was moved between a busy downtown square and a public park. Participants tended to check on their sensors ("*I'd pass by it several times a day to see if it's still there*", P4), and most locations were motivated by finding contrast:

> I think a lot of it was going for the contrasts… to compare what we perceived would be really high with something that would be pretty low. (P2)

Unlike other groups, activist planned to keep using sensors after the study, for instance to test air quality on the river ("*we should rent some kayaks and just take them* [sensors] *out for a day and paddle around*", P1).

Visibility and attention

To varying degrees, participants expressed a tension between sensor visibility and theft and ownership of space. The activist participants were most comfortable with visible sensor placements and were not intimidated by 'suspicious' looks unless police were involved ("*I'm sort of used to doing ridiculous things in public, but I'd wait for a cop car to go around the block*", P1). Cyclists tried to avoid loosing sensors early in the study and first concealed their placements ("*I kinda wanted to get it back, so I kind of like hid it on the other side*", B4). However, later in the week, B2 placed the exhaust sensor more overtly to explore "*the social aspects of the study*":

> The last time I placed it, I definitely wanted it to be found. I didn't wanna loose it early, 'cause then I thought I wanted to kinda take it around a few places but at the end I just wanted to see what would happen. (B2)

Similarly, homeless participants placed the exhaust senor in visible spots near bus stops: "*right in* [front of] *everybody, where the buses pull up, right near the stop, boom it's there*" (H3). Below, H2 highlights the importance of visibility:

> I woulda put it up somewhere where it would be visible to everyone so if they read on the back of it, they woulda know the website and stuff like that, and got more data off that if they went to the computer and seen that. And they would've probably moved [the sensors] themselves... and so that could be moved around like- just having more people into it. (H2)

Parents, too, wanted more people to "*be interested in it* [project]" (P2), and even suggested cameras to record public reactions to the sensors. At the same time, parents also highlighted trying to avoid sensor loss (*"I didn't want them to be taken, but I wanted them to be in a place that's open",* P3; "*I purposely hung it higher up, but it was completely visible*", P1). Not surprisingly, parents were disappointed by the police interruption, describing the incident as both amusing and sad:

> It seemed so funny that it happened so quickly… [it] makes me a little bit sad because I guess that's how people view themselves as being good citizens now, and reporting terroristic threats, when if they had half a brain, they would think the Rite Aide in [city omitted] is not a big target. (P3)

Ownership and permission

Perhaps in part prompted by the police incident, parents touched upon issues of ownership and access. P2 felt a sense of ownership over a public parking lot in her neighborhood:

> P1: I wonder if they [Rite Aide] owned it [the space] or not.

> P2: Well, I didn't think of it in that way, because we can go park in their space so I thought we could do this… I thought, 'it's my neighborhood'. If I put it on the street that would've been municipal property maybe…

In another instance, P1 explicitly asked for permission to place the VOC sensor at a paint factory: "*there was a moment when he was concerned… maybe he didn't want us to find some dirt on him or something*".

These approaches (asking for permission or having a sense of ownership) contrast H4's behavior, a homeless participant who wanted to avoid drawing attention to himself and the VOC sensor he placed in the park:

> Somebody may have asked me, like you know, this isn't your property this is private property. (H4)

To summarize, the four groups expressed different views on sensor placement, visibility and ownership. While activists had a highly-coordinated plan for placing sensors and reached out to other local communities, parents were concerned with sensor security and ownership of space, cyclists tended to carry the sensors with them throughout their 'journeys', and homeless aimed to put sensors in visible locations without drawing attention to themselves.

Data exploration

Participants from all groups used the data visualization website several times over the course of the study. Initially, cyclists used the map as tool for tracking where they had been rather than exploring air quality:

> I was more interested in what you guys were doing, like your movements, not exactly the data, I didn't look into it. I just wanted to see where you guys had been. (B2)

Tracing their movements, cyclists noted that the data made them to want to move around more, "*making a web around the city*" (B4). Likewise, parents were especially interested in placements chosen by others in their group, and less concerned with the data, "*particularly because I never saw a high reading anywhere, so it didn't seem like the reading itself would be interesting*" (P3).

On the contrary, homeless participants were mostly interested in their own sensor ("*I just looked at mine*", H5). However, sharing a computer at the shelter with others made data individual exploration difficult ("*I have to sit there to figure out what I'm looking at but he'd just keep moving it [the website] around*", H2). Homeless participants were most surprised to see low/moderate readings from the sensors:

> I was expecting it to be higher, cause the exhaust you know... it's not one bus, it's several buses are passing or stopping there. So I was expecting it to be like off the chart. (H3)

When reflecting on the data gathered over the course of the study, all groups became interested in anomalies, patterns and comparisons. Cyclists, for instance, focused on re-occurring peaks in exhaust and VOC data ("*I didn't think that there'd* *be such a distinct hump* [in exhaust data] *at rush hour, that's cool*", B4; "*oh wow, that's [VOC peak] really early in the morning*", B2). Parents noticed higher exhaust values in some neighborhoods ("*where you* [P3] *put it, was higher*", P1). Activists also liked being able to compare data from different locations simultaneously ("*I do like how you can hold one* [info window*] open and then sort of compare*", A3). Moreover, they wanted to see data from all sensors along the same graph and compare longer-term data: "*I'm curious if the level of pollution goes down in the winter*" (A1).

Unlike the other groups, activists also tended to remember specific readings ("*It was about 40* [VOC] *at my house*", A2; "[exhaust] *was higher at the children's hospital*", A5; "*I thought there'd be more dust on the street*", A1). They commented on micro-level data for different areas:

> Whenever they put out air quality alerts, it's like a blanket thing… But if you're like way outside of [the city] up on a hill, it's probably not as bad as at the bottom of the valley, downtown. Being able to see the actual nuances of that difference is really important. (A3)

With this level of attention to the data, it is not surprising that activist participants were more curious about the scale for the data than other groups ("*does 100 mean that you're literally breathing in nothing?*", P1).

Data sharing and activism

The four communities expressed different views about data sharing and activists. On one hand, cyclists wanted to broadcast the data via the sensors themselves, especially as a graph over time or in comparison to other locations such as parks:

> B4: If it had that on it, then I would put it in really visible places as opposed to kinda tucking it behind a corner
>
> B2: Then you're making a statement
>
> B4: Cause then you're trying to say something

Cyclists also suggested showing data to students, particularly environmentalists who could interpret and present it more concisely to the public.

Parents, on the other hand, were more hesitant to share their data because they were not sure of its scientific value. They wanted to know "*what it means before showing it… at what levels does health become impaired*" (P1), and wanted to gather "*more data, collected in a more… scientific experiment"* (P3).

Homeless participants did not feel compelled to act on the data either, but for different reasons. H5 felt that nothing could be changed ("*there's really not much you can do about it*"), and H3 pointed out that sensor values were not high enough to pursue any action in the first place. If given the opportunity to broadcast the information, the homeless suggested showing it downtown ("*because that's where everybody has a tendency to cluster*", H4), as well as to college campuses:

College students are the future of this country. They're the future bosses, the fortune 500 companies, congressmen, senators, congress women, mayors, whatever… they need to know a lot of this stuff, better to get knowledge of it now than when a student becomes a senator, or whatever. (H3)

Activists were most enthusiastic about sharing sensor data. During the study itself, they discussed the project with a local farm collective:

It was pretty cool just to explain to people what was going on with it. Like we went down to [the farm collective] and we were like 'Look, you've been trying to get an idea of what's in your air for like years now and now we have a way for you to check it and it's free. Do you want to check your air quality?' And they were like sure, that sounds good. (A3)

Individuals from the urban farm collective reportedly wanted to use all three sensors for longer periods of time ("*they wanted all three [sensors] there for like an extended period of time to get some long-term data,"* A4). Activist participants also discussed the study within their community:

A lot of the people that I talked to were really into it… I think if there were a lot of sensors around the city and this website up… a lot of people would want to check it. (A2)

In the future, the activist group wanted to share data with people from the neighborhoods where they placed the sensors ("*the people who live and work around those areas- people who spend a lot of time there*", A3), as well as other activist groups ("*if there is a group of people that could do something about the air quality*"), and those most affected (*e.g.*, "*I want iron workers to know what they're inhaling*" A1). Activists also wanted to broadcast the information at the children's hospital:

By the children's hospital, I really wanted that like a display board, like look- 'it's a children's hospital, how much toxic stuff is in front of and on the side of this space.' People who bring their children to the hospital should know that (A6)

Finally, activist participants wanted to identify causes of pollution to catalyze action:

It would be interesting to see who bears the most responsibility for that and then if you can sort of specifically get a group of whoever's contributing disproportionately or the most to the problem, then you can start doing something about it. Like a campaign or something like that. (A3)

3.3.4 Summary: community concerns, activism and sensor use

Bicyclists and parents split the sensors (per person or by days of the week) using them independently and tracking each others' placements on the website. These uses reflect approaches for addressing group concerns: our bicyclist participants prefer independent acts (graffiti or murals) to "*beautify the area*", while parent participants defer to advocacy groups for changes in urban.

The homeless are a community by circumstance rather than choice, with each person having "*some type of business to go to, to get up outta here*". Their sentiments of powerlessness and resignation ("the five of us couldn't change our legislation if we wanted to") in response to mutual concerns (housing, jobs, etc.) echo their lack of coordinated 'strategy' for sharing the sensors: each person took and checked data from whatever sensor was available.

Conversely, the activist community revolves around group action—free food distributions, rallies, lockdowns, etc., to resolve issues from a "*list that we've all agreed on"* (capitalism, oppression, etc.). Consequently, they adopted the study as a conjoint practice, moving communally-shared sensors and discussing data as a group. Our findings highlight a range of group appropriations and interpretations of our system, and we emphasize adoptions of sensing systems as reflections of community structures, values and concerns.

3.3.5 Limitations

We intentionally chose low-end sensors and did not pursue precise calibration procedures, positioning our system as a tool that can be implemented by non-experts. Consequently, our website visualizes relative measurements across time and space (values ranging between 1-100), and all four groups commented on the scale, wanting to know how harmful the levels are for their health. However, lack of absolute values did not deter participants from exploring, reflecting on, and reacting to the data. The homeless focused on individually-collected data ("*I just looked at mine*"), expecting it to be "*off the chart*". Other groups were interested in comparisons: bicyclists looked for a "*dependence of time*", tracking "*humps*" that correlated to rush hour; parents and activists compared locations ("[exhaust] *was higher at the children's hospital*", "*where* [P3] *put it, was higher*", etc.) Moreover, participants, especially activists, wanted a longer-term deployment. Battery life is an inevitable constraint for physical systems, and future work can explore different power sources (solar panels, casing that allows battery recharging, etc.), as well as related research questions: what happens during prolonged deployment? Do sensors become convivial tools?

3.4 Design implications

Findings from the preliminary sensor probe study and the functional system deployment suggested several design implications for interaction design. Both studies emphasize participatory place-based sensing not merely as a passive act of measurement, but as a powerful resource for community-wide expressions and activism. Public sensors can indeed become mediums for 'projecting' stakeholders' concerns into the public sphere and exposing ('tracing') the circumstances that have led to the current state. As such, sensors become instruments of defiance and transformation of space, leading to community-wide awareness, togetherness, and ultimately—the construction of active 'publics'.

3.4.1 Sensing as engagement with space

Our findings show that sensing, whether in the abstract form of non-working probes or as a system of fully functional air quality sensors, inspires people to reconsider and engage with public space. Some spaces afford similar interpretations across communities: public bathrooms evoked concerns about pathogens; bus stops and busy intersections were associated with exhaust sensor placements, parks inspired pollen measurements, and factories/construction sites raised concerns about dust. Other spaces, however, evoked different interpretations: parents placed a pathogen probe onto store counters and shopping carts; activist participants reached out to a local farm collective with functional sensors or monitored VOC's by an iron apprenticeship; students were interested in pesticide levels in a parks, and cyclists wanted to monitor all pollutants near community meeting spots and hangouts.

Reflecting on sensor placement as an act of demarcating a place to be sensed shifted participants' perceptions of spaces: they became more aware of dust at construction sites or germs on door handles, (*e.g.*, "*I noticed more dust and stuff*") The interplay between community values and spatial affordances leads to different interpretations of public space across communities, suggesting that there is no 'one size fits all' universal sensing system. Instead, future technologies must tailor to specific community interests and needs, supporting participatory sensing as an approach for community-based engagement with public spaces.

3.4.2 Environmental data as a form of social currency

Our participants discussed 'sensor data' as an artifact that could be shared, broadcast, or articulated within and across communities. For parents, this information served as a tool of community togetherness: they wanted to share data with other parents, presenting it through school award ceremonies, children's sporting events, school websites, *etc*. Unlike the parents, homeless participants wanted to anonymously broadcast this information to the general public by making the sensors more visible, or conveying the information through notes and flyers. Perhaps by showing passengers that a bus contains germs or by proving to pedestrians that exhaust levels are harmful, the homeless hoped to incite public activism that they themselves do not feel empowered to partake in. Students, on the other hand, saw the data as an opportunity to personally negotiate dialogues with policy makers: they suggested ways to present data directly to local officials and authorities. Lastly, activist participants used sensor data to reach out to other communities (*e.g.*, the farm collective).

Reframing sensor data as a form of social currency suggests a need for data visualizations that engage stakeholders beyond traditional charts, graphs and colors. For tighter-knit communities such as parents and activists, sensing can serve as tools for community togetherness, facilitating data exploration as a *conjoint practice*. Community-specific visualizations can enable groups to track where friends put sensors, compare measurements between neighborhoods, or explore trends over time. For other groups such as the homeless, interfaces could broadcast personal concerns in ways that appeal to the general public, who in turn can serve as an intermediary between the stakeholders (*e.g.*, homeless) and the government. New technologies could also empower direct communication between citizens and policy makers through mechanisms that provide feedback, as was suggested by the student participants.

Finally, sensor data can become a boundary object to engage different social groups. For instance, while the presence of 'hobos', raised safety concerns for bicyclists/students, the homeless considered students to be the "*future of this country*" and a receptive audience for sensor data. How would students' perceptions of 'hobos' change if data collected by the homeless was projected to a university campus, and vice versa? Instances of group sharing might be welcomed (the farming collective wanted all three sensors) or rejected (a paint salesman "didn't want us to find some dirt on him"). Digital spaces can make intentions and consequences more transparent, empowering groups to collaborate towards desired outcomes. Such technologies can serve as instruments of persuasion for community concerns, linking people through their actions (Dourish, 2010) as opposed to comparisons of individual behaviors.

3.4.3 Sensing as active transformation of space

The act of placing a sensor is a public statement and the presence of a sensor broadcasts a citizen's concern about a particular space. Whether to inspire interest of "people musing over these things", or to broadcast air quality in front of a children's hospital with "a display board", and bring "more people into it", participants wanted to use sensors to project a message into a space. Parents used pathogen probes to draw public attention to dirty toilets, the possibility of lice on theatre seats or bacteria on un-emptied trashcans. Bicyclists placed exhaust probes in parks and bike lanes to raise questions about the impact of surrounding traffic on air quality. Students put chemical probes near sewers to highlight possible contamination of the water supply. In placing sensors throughout their daily routines, participants physically labeled each space with specific concerns. The impact of these 'tags' remains to be explored: does an exhaust sensor reroute foot traffic, or does it signify a safer, cleaner area because of the in-place monitoring?

As sensor output and placement becomes increasingly important, we argue for including stakeholders in the design of sensing systems, from the bottom up. Groups such as homeless, for instance, may prefer inconspicuous devices to avoid attention during the act of placement, with the ability to remotely trigger a display that broadcasts data to the general public; other communities may build visualizations to target specific stakeholders (neighbors, iron workers, *etc.*) or track social aspects. More broadly, open source platforms can empower communities to create visual and material form factors, altering output modalities based on their needs.

3.4.4 Ownership, access and security

To varying extents, our study exposed all participant communities to issues of security, privacy and authority. Stakeholders navigated tensions between authorship and theft, placing sensors "*higher up but completely visible*" or entirely concealing them in trees or "*behind a corner*". From asking for permission and explaining the study, to placing sensors covertly, to assuming ownership of space, to ignoring 'suspicious' looks or defying authorities altogether, communities reflected on notions of private, public, and authorized space. For parents, these tensions were explicitly foregrounded by a police intervention.

Although our sensors were clearly branded, in a post 9-11 world, homemade DIY objects that would have previously been considered interesting, provocative, or eccentric can now be perceived as threatening. Increased surveillance as encouraged by the Department of Homeland Security warning to "*be vigilant, take notice of your surroundings, and report suspicious items or activities to local authorities immediately*"[20] has shaped and constrained artistic, academic and whimsical endeavors over the past decade (for instance, the Boston Bomb Scare[21]).

Our experience with the police reveals interesting considerations for public sensing: while theft and vandalism were major concerns across all four groups, the only sensors damaged during the study were due to police intervention; and despite suspicious glances and police presence, participants continued to pursue overt and public sensor placements- near hospitals, factories, bus stops, etc. We cite these findings not as reflections on law enforcement, but as points of engagement with issues of perceived safety, privacy and ownership. Participatory sensing places new tools in the hands of ordinary citizens, inevitably exposing the general public to unfamiliar technologies and contexts. The boundary between 'evocative' and 'threatening' remains unexplored, and the police (an under-studied community in HCI) may offer valuable insights for this domain. While we readily carry personal electronics and talk of a ubiquitous computing future, publically-placed technologies and sensing is fraught with a myriad of challenges – namely those embedded within a culture of fear. Future research can focus on design factors such as enclosure shape, color, texture, and sensor legibility to lessen such public concerns.

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[20] http://www.dhs.gov/files/reportincidents/counterterrorism.shtm
[21] http://www.cnn.com/2007/US/01/31/boston.bombscare/

3.5 Conclusion

This chapter explored the concept of public place-based sensing amongst urban communities. Stakeholders' use of and reflections on hypothetical sensor probes inspired our design of fully-functional sensors. These sensors report air quality along with weather data to a server that displays the information on a website in real time. Our deployments with groups of urban stakeholders—parents, bicyclists, homeless, activists, and students—suggest place-based sensing as a tool for community activism. Throughout the studies, the hypothetical and real sensor data was discussed as a resource for parents to act together with other parents, for homeless to speak to and incite action from the general public, for students to negotiate for change with the policy makers, and for communities such as our activist group to collectively act alongside other groups. These findings reveal design opportunities for environmental data as a form of social currency and physical sensing systems as instruments for expressing matters of concern.

4 Balloons and WallBots: tools for public expression

This chapter continues to explore sensing as an approach for bringing communities together around shared concerns and catalyzing public engagement with local issues. Building on related research on DIY practices, as well as the previous chapter's implications to involve stakeholders in the design of sensors from the bottom up, I present two systems for expressing matters of concern through *spectacles*[22].

I define *spectacle computing* as a strategy for vibrantly expressing information through the use of tangible media for public engagement and reflection (Fig. 4.1). Contrary to contemporary rhetoric of "invisible" interfaces and seamless computing, this complementary strategy is explicitly designed to generate spectacles. First and foremost, spectacles are difficult to ignore. The barrier to engagement is thereby effectively lowered because individuals need not download an application or carry specific hardware. The spectacle is intentionally designed

Figure 4.1. Air quality balloon installation in public park.

[22] Parts of this chapter were previously published (Kuznetsov et al., 2011; Kuznetsov et al., 2010)

to distract the individual or group's attention. Moreover, it invites people to engage in otherwise socially unacceptable behaviors such as overt public voyeurism, gossip and curiosity. Finally, it presents an acceptable context for individuals to participate in the spectacle, in the spirit of a Happening (Kaprow, 1966), even if such participation involves odd, unusual, or socially awkward activities (i.e. willingly taking and carrying around a glowing balloon or interacting with a wall-crawling robot).

To be clear, spectacle computing is not designed to mimic the experience of yelling "fire" in a crowded theater, but to more deeply and expressively engage public audiences in issues of personal or societal concern. While this approach is tangentially related to FlashMobs, which draw large groups of people to suddenly assemble and perform unusual acts in public places, the goal of spectacle computing is to foster discourse between stakeholders, technology, and space through the use of dynamic computing elements. Also unlike FlashMobs, which may create a feeling of inclusion and exclusion, spectacle computing invites open participation from everyone.

I first explore this idea with an inquiry into existing practices behind public expression. I introduce WallBots—autonomous, wall-crawling robots, as a research probe in a study of individuals who extensively contribute to public spaces through street art and political activism. The WallBot is framed as a low-cost DIY authoring tool for public expression across a wide range of surfaces and hard-to-reach places, including bus stops, whiteboards, streetpoles, trashcans, moving vehicles and building walls. The study of WallBots with six public artists and activists reveals insights into the materials and practices behind grassroots public expression. The second half of this chapter builds on these findings and offers an example of spectacle computing with large, glowing balloons that change color based on surrounding air quality. I packaged the project into a DIY kit that enables people to assemble their own weather balloons that change color in response to input from attached air quality sensors (exhaust, diesel, or volatile organic compounds).

This chapter's contributions are twofold. First, the work presents DIY sensing methods that can be easily assembled from off-the-shelf components. Second, it shows a departure from more traditional visualization techniques such as charts and graphs to show air quality in two radically new ways: first by presenting wall-crawling robots as a vehicle for expression in hard to access spaces; and second, with glowing balloons as a vibrant, overtly public and playful medium. The study of WallBots and deployments of air quality balloons reveal design implications for DIY, tangible interactive systems as an approach for expressing public concerns.

4.1 Interactive wall-crawling robots in the hands of public artists and activists

Public spaces present a natural canvas for expression, provocation and creativity. City streets worldwide have a rich history of fostering artistic and political subcultures, from graffiti artists, to street performers, to environmental activists, challenging our notions of anonymity, authorship, physical boundaries, political freedoms, and social convention (Gastman et al., 2007). Whether we like it, hate it, or ignore it, street art plays into urban aesthetics. It shapes the way we feel and engage in the spaces around us.

So who are the people that tape posters to streetpoles, paint murals on buildings, spraypaint words in underpasses, and sing in subways? What are their goals, their challenges and their values? And how can we, as HCI researchers contribute to the practices that shape our cities? With the convergence between grassroots public expression and low cost technologies, HCI research has focused on tools for authorship in public spaces (Höök et al., 2003; Brynskov et al., 2009; Minneman et al., 1998; and others). This chapter explores opportunities to engage the graffiti artist, the street musician and the activist in the design of interactive systems for public expression.

I present WallBots, autonomous magnetic robots that can freely traverse any vertical steel surface, as a research probe for activating a range of public spaces and 'third-places', including bus stops, hallways, trashcans, streetpoles, elevators, stairways, *etc.* (Figure 4.2). Built entirely from inexpensive off-the-shelf parts, WallBots can be easily replicated and modified by non-experts, allowing artists, political activists and general hobbyists to leverage wall-moving robots as a novel platform for expression and authorship. While broader public expression is my long-term goal, this chapter explores the role of early adopters and "skilled city authors" such as artists and activists in engaging with such novel technology. I evaluate WallBots in a study of six individuals who already contribute to public spaces through graffiti, paint, street music, political flyers/posters, and light graffiti.

Figure 4.2. WallBots deployed on public surfaces.

4.1.1 WallBot design

We developed two prototype magnetic robots that we call WallBots. These robots have two wheels with (commercially available) magnetic disks glued around each rim, allowing WallBots to defy gravity. Wheel rims are covered with silicone paste to increase traction as robots traverse vertical surfaces in any direction. Acontinuous servo motor drives each wheel, as two rechargeable lithium batteries power the robot. WallBots are controlled by an Arduino Mini—an open microcontroller that is widely used in numerous art projects for its flexibility and easy programming (for example, to control Jackoon an artbot that paints on horizontal canvases; Torres, 2009). A custom circuit board to connects and houses the electronics, allowing for accessory sensing and expression capabilities, as additional electronics can be attached directly to the board. For instance, our PCB design includes slots for a BlinkM—a powerful controlled tri-colored LED that can be easily programmed for any color, pattern or fade sequence to express the WallBot through light. The back of the board houses slots for LED's, which we have implemented as tail lights to playfully indicate WallBot turn direction.

In addition, our board leverages Arduino's analog pins such that any four sensors can provide input to the WallBot (light, noise, tilt, temperature, etc). Our first prototype, includes four photoresistors (light sensors), placed on the front-right, direct-front, front-left, and top of the robot (Figure 4.3). Continuous sampling from these sensors enables robots to detect light gradients in the environment and react to hand gestures. WallBots are programmed with a USB-TTL cable, which connects directly to our PCB.

WallBots in the context of street art

We envision WallBots as a technology that can be easily replicated, modified, and deployed by public artists and activists. Given the low cost, easy construction and flexible (programmable) behavior of WallBots, we position our technology as an authoring tool for people who shape our cities through art and political activism. In doing so, we aim to open a broader dialogue between HCI research and grassroots public expression. I continue with an exploration of the current practices, methods, and motivations of public artists and activists.

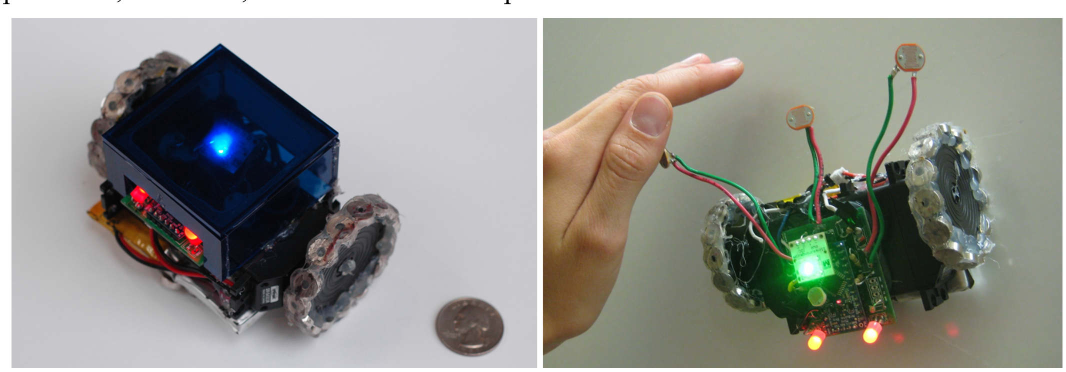

Figure 4.3. WallBot with case and WallBot on a wall with sensors exposed.

4.1.3 Urban expressions: practices and methods

To gain insights into the processes that drive public art and activism, we conducted a study of six participants who extensively contribute to public spaces. The study consisted of semi-formal interviews that investigate three themes: 1) participants' current work, goals, and obstacles in public spaces, 2) participants' expressions across eight surfaces that could serve to house WallBots, and 3) participants' evaluation and appropriations of WallBots and interaction techniques that could be used to control them. Participants were recruited through an online bulletin board (Craigslist) and compensated $10 upon completing the interview, which lasted for about an hour.

Participants

Our 6 participants contribute to public spaces for political (P2, P3), artistic (P1, P4-6) and/or financial (P6) reasons (see Table 1 for participant details and Fig. 3 for examples of their work). P1 has been doing graffiti for over 10 years, "*from hand-tagged stuff to full-on graffiti*"; P2 and P3 post flyers and posters for presidential campaigns and local projects (*e.g.*, "*save our libraries*"—to keep local libraries open); P4 paints "*with light in a long-exposure photograph, and the whole time I'm moving light around and it's creating an image*"; P5 works with a variety of materials, including typewriting poetry on tree leaves and "leaving them anonymously in places", spray-painting stencils, graffiti, and flyers (*e.g.*, Buddhist Thoughts) with a "*wake up now, life is now*" message; and P6 plays guitar and sings, often busking—performing for tips especially in "*affluent, south of the city suburbs*". None of the artist participants have political agendas ("*I try to stay out of it, I'm not a big fan of politics*", P4; "*I just believe in love, peace and harmony and that's not political*", P5), contributing to public spaces for self expression or public attention. In addition, the street musician (P6) is motivated by money: "*It's a balanced interest. The money is great, but it's also fun, summer memories*".

Participants tend not to use their real names during public expression, however P1 and P5 sign their work with a symbol: "*I have a symbol that I use, that I think people recognize*", and P4 often writes "*the name that I have for my website*" P4. P1 is particularly inspired by hard-to-reach places "*climbing places, rooftops, the most inconvenient places that you would ever expect to see it*", enjoying peoples' reactions:

> I kinda like when people are walking down and they see something like up on a roof… up high- the higher the better. People will be surprised when they see it: How the hell did he do that, how did he not fall, how did he not get caught… (P1)

P5 also observes public reactions, for instance:

> I took straws and I hung them around different places outside in a city and they just said breathe… it was so fascinating to watch people interact with them…. Some people would stop and [inhaling emphatically] take a deep breath and that was kinda the point. (P5)

P2 and P3 gage the effectiveness of their flyers based either on rally turnouts (*e.g.*, "*we had such a turn out—without all the flyers notifying people there is no way people would've known about it*"), or direct observation: "*some people stopped there and then read a little bit and then turned away—maybe to register to vote or something*" (P2).

Conflict with Authority

To varying extents, all participants experienced tensions with authority. P1 and P5 were most affected:

> Graffiti is kind of like a rush to me, there's always that risk, you could get seen, you could get caught, you never know when someone could come up behind you… (P1)

> You have to be careful in America because they'll arrest you and put you in jail… I find myself resorting to sides of buildings or places where I have more coverage. (P5)

In the past, P6 and P4 have both been "chased out" or "kicked out" by the police (*e.g.*, "*I tried the PPG [skyscraper] place before, but security is a little tight, apparently you're not allowed to have a tripod there. I think it's like an anti-terrorist thing, I've been kicked out of there more than once*", P4). To a lesser extent, activist participants faced similar problems: "*sometimes the management or facilities just strip out all the posters and so mine is gone too*" (P2), or in the context of permission to place posters: "*some businesses are just kinda like, yea it's a great idea but we don't wanna junk up our wall or window or whatever*" (P3).

Materials and Money

Participants tend to create or repurpose their materials. The activists usually design and print their own posters. P5 prefers "*taking things from nature*", not killing anything but using "things that are already on the ground" (eg., printing poetry on dead leaves), as well as recycled materials such as straws or shredded paper. P1 either makes paints from scratch (using simple household products for instance) or receives materials for free: "*never spent a dime, either making my own stuff or coming about companies online that make certain types of markers or certain types marking materials or paint*", and asking companies for free samples of their products. P6 also highlights the importance of money: "*On a good night you can make like 50 bucks playing for a couple of hours*".

4.1.4 WallBots in the hands of artists and activists

The second part of our study asked participants how they would use WallBots if these robots were available for free or at a low cost. Participants tended to discuss ways by which they would personally repurpose WallBots for their needs, using words such as "attach", "make", "fix", "build", "command", and "program". P5 also verbalized (without prompt) that "*if you wanted to empower people and for them to use it, then yea make instructions and make it available*". I now present participants' specific suggestions for our technology in the domains of street music, graffiti, political activism, and light-graffiti.

Graffiti

Graffiti art is constrained by political and spatial boundaries, often aspiring for physically inaccessible and socially or legally forbidden spaces. The practice itself is hidden, but the work strives for attention, permanently embedded on any surface that can be reached without getting caught. As one of the most defiant forms of street art, graffiti thus invites WallBots for their "*factor of invisibility*" (P5). Having a robot that creates graffiti "*changes everything because it places the responsibility in an invisible place. I like that about it*" (P5).

In addition, both P1 and P5 also naturally saw WallBots as a tool for placing art in higher, hard-to-reach spaces: "*I'd try to attach something to it and I would put it on a wall that's a little bit higher- harder to reach by ladder…*". Lastly, P1 noted that the WallBot itself is a type of graffiti:

> I'd leave it in a public place just for people to see. It is almost like graffiti, it's gonna catch the attention— they're gonna almost be in that awed state— oh wow what is that. (P1)

In short, autonomous wall-crawling robots present opportunities for drawing attention to the work without exposing the artist. This attention could be achieved both by enabling artforms on harder to reach spaces (heights, fenced in areas, etc), as well as by the unexpected presence of the technology itself (i.e., the WallBot as a 'type of graffiti').

Street Music

The street musician is almost diametrically opposed to the graffiti artist, aspiring to draw public attention to the act of authorship rather than its lingering aftereffects. His or her relationship to the space is temporal, and the spatial contribution—ephemeral. It is not surprising that P6 saw WallBots as a means for holding a captive audience, to "*add something to the performance— so if there's a way to program it so that it kinda fits what you're doing*". In particular, P6 proposed using WallBots to make performance more interactive:

> Sometimes you feel like you're doing something and people choose to watch… if they just want to listen they're not really interacting, but if there was something else to hold their attention that might be useful. (P6)

In the 19th century, the organ grinder beckoned crowds with a performing monkey. Today, technologies present a low-cost, DIY and better-behaved alternative. Autonomous agents form a creative extension of the artist, suggesting opportunities for live interactions between performer, audience and machine.

Political activism

For the activist who can freely post flyers on the most visible surfaces (bus stops, streetpoles, etc), it is not enough for a message be noticed. Its placement and content must compel the viewer to vote, to attend a rally, to call a local official, to *react* in ways that further the activist's goal. Urban spaces become mediums of persuasion, challenged by public apathy and lack of awareness. Hence, both of the activist participants suggested using WallBots to express messages on larger-scale surfaces, as well as higher up:

> To be able to command it beyond where you're able to normally reach. You could set up a scaffolding or you could bring a robot and tell it what you want it to do. (P3)

In addition, P3 noted that the act of using a WallBot would be effective in itself:

> It would be such an attention getting thing. You have 100 flyers up but if you have a robot telling your story… (P3)

Here, magnetic kinetic systems present an opportunity to engage the viewer in political dialogue, to combat ignorance with insights into the cause and to transform indifference into action. The robot must therefore 'tell the story', enabling a message to evolve through space, fluidly engaging the observer with direct and implicit interactions.

Light graffiti

The light painter draws in plain site, but his work is invisible: sketching in the air, on building walls, trashcans, bus stops, or park benches, he creates designs that are only captured through the lens of his camera. His paintbrush is a flashlight, a glowstick, a match, a light pen, a candle—with these he flirts with space, developing a relationship that is both fleeting and permanent. Light painting is inherently constrained by accuracy, as P4 explained:

> When you're drawing in the air or whatever, you can't see what you've already drawn, so accuracy is very limited. I can't go back and touch something up, see where a line started to finish it.

Having robots with built-in lighting empowers long-exposure photographers to capture precise designs that can not be hand-drawn. To achieve this effect, P4 suggested making the WallBot larger and adding an attachment for a light source.

> The potential applications for what I'd do [with WallBots] is just the next level—like it's between me scribbling in the air and recreating the Mona Lisa. (P4)

Kinetic systems can thus converge with the craft, liberating the light painter from his greatest challenge: precision. Autonomous agents, wielding a range of light 'brushes' from bright LED's to luminescent bulbs or flaming torches, may be programmed to create intricate designs that can not be achieved by hand on surfaces that previously remained inaccessible.

4.1.5 Discussion

These findings suggest a complex range of values, challenges, and practices for public expression. I conclude this section by highlighting four themes that emerged as essential for all six individuals who routinely author public spaces: anonymity, authorship, appropriation of space, and DIY methods.

Anonymity

To varying extents, all participants work under a veil of anonymity: they do not use real names, and most place their work and step aside, watching people's reactions from afar. Much can be said about this paradoxical desire to remain invisible while placing content in the most visible spaces. Naturally, P1 and P5, who author spaces with graffiti, spraypaint, and other permanent mediums, are most concerned about getting caught. Legal constraints shape their practices, positioning graffiti on the "lower" parts of bus stops, causing artists to work faster on lit streetpoles, and avoid certain surfaces altogether (i.e., elevators with cameras). The work of a street musician embodies anonymity in a different sense. The practice (playing music) is itself in plain site, but its temporality leaves the artist unnamed: when a performance ends, the space is reclaimed as if the music was never there. From this stems the street musician's greatest challenge: he must compete with traffic, noise and general apathy to draw a crowd amongst strangers who know him only through his ephemeral contribution to the space, here and now. These practices of remaining nameless lead to interpretations of WallBots as tools of "invisibility" that allow anonymous placement of content, possibly through interactions that are implicit, removed from the robot, the surface, or even the space altogether.

Authorship

While public activists and artists remain unnamed, they symbolically claim authorship of their work and thrive on public attention. The graffiti artists (P1, P5) and the light painter (P5) sign their pieces with a symbol that is known and recognized throughout their communities. Moreover, all six participants enjoy eliciting reactions to their work: from shock and admiration of reaching a high space, to causing someone to stop and 'breathe', to increasing rally attendance or voter registration, participants want to impact and shape their environment. This desire to restructure public spaces inspires participants' appropriations of the WallBot as a means of drawing attention. For the graffiti artist, the WallBot is a tool to access a higher, more 'surprising' place; for the light painter, the WallBot serves as a precise 'paintbrush'; for the street musician, the robot morphs into an interactive performance accessory; and for the activist, it communicates across larger surfaces, becoming part of the message itself.

Appropriations of space

All six participants are against altering what they perceive to be personal space-avoiding graffiti on "private cars" or residential homes, not performing in public transport where people can not 'opt-out', and feeling compelled to ask for permission to post flyers on building walls. At the same time, participants consider spaces such as bus stops, street poles, elevators, and corporate buildings to be acceptable sites for expression. The "foot traffic" associated with these spaces is both an asset and a challenge—a political message might be noticed, but a graffiti artist may get caught and a street musician might be ignored. Moreover, some participants' use of space reflects societal rules: while a garbage can serves as a canvas for graffiti and light painting, a political flyer placed on the same medium may suggest negative implications for the message. Issues of access, privacy, and social convention cause participants to interpret WallBots as robots that go where people cannot.

DIY methods and mentality

Given that all six individuals reshape public spaces, it is not surprising that they also choose to create, repurpose and reuse the tools and materials that facilitate their expressions. While for P1, DIY is a means to save money on paints, markers, etc., for P5 reuse becomes an artform in itself, turning shredded paper into a "dancing flurry", or dead leaves into a medium for poetry. Because participants tend to create or alter the materials they work with, they perceive WallBots as artifacts that, in their words, they can "fix", "make", "command", or "attach" things to. Rather than being viewed as mere tools to perform a task, WallBots are welcomed as part of the artform itself, interpreted as "little messgengers", "performative", "dancing or reacting to music", or a means to "connect" people around the world if they create content through the same means.

To summarize, this section presented an exploration of the methods and practices behind street art, constructing a dialogue between HCI research and the values and processes that underlie public expression. WallBots—autonomous, wall-crawling robots—served as a research probe and an approach for novel expressions on vertical surfaces. Placing WallBots in the hands of public artists and political activists reveals a design space for magnetic kinetic systems as a medium of public expression, persuasion, and performance.

4.2 DIY air quality balloons

With DIY, appropriation of space, anonymity, and authorship as key points of tension for public expression, I now present air quality balloons as a spectacle computing system for projecting citizen concerns into the public sphere. This system demonstrates how spectacle computing moves people from a personal and private context, through public voyeurism, and into readily carrying balloons around the city, thereby authoring public spaces and potentially creating spectacles.

There are many reasons for choosing balloons as an expressive medium. Balloons are inherently playful: they remind us of birthday parties, water balloon fights, street fairs, weddings, or carnivals. Balloons are also functional: for decades they have enabled scientific endeavors, ranging from the NASA superpressure balloon which successfully flew over Antarctica[23] to the National Weather Service radiosondes (sensor packages) deployed on weather balloons[24], as well as many grassroots aerial photography projects (*e.g.*, Brynskov, 2010). Lastly, balloons are compelling and visual: they have shaped artistic and political expressions, including the popular song 99 Luftballons (1983), Lamorisse's film The Red Balloon (1956), the literary work More Sky (1973), and most recently, interactive balloon installations such as Open Burble (Haque, 2003). This vast range of artistic and functional balloon projects inspired me to utilize large glowing weather balloons as a playful expression of a serious concern—public air quality. Moreover, balloons are relatively cheap and easy to integrate into the environment.

4.2.1 DIY air quality sensing kit

I created a DIY sensing kit that vibrantly visualizes one of three types of air pollutants: diesel, exhaust or VOC's (volatile organic compounds). These three pollutants continue to exacerbate urban air quality problems, especially in the city where we conducted this research, where air quality has been rated as among the worst in the United States (American Lung Association, 2010). Diesel exhaust consists of fine particulate matter emitted by engines and industrial processes (U.S. EPA 2002); exhaust gas—a mixture of carbon monoxide, nitrogen dioxide, and hydrocarbons—is produced by gasoline engines (Coalition for Clean Air); and VOC's (volatile organic compounds) originate from paints, pesticides, or certain types of fuels (U.S. EPA 2002). Exposure to any of these substances can lead to

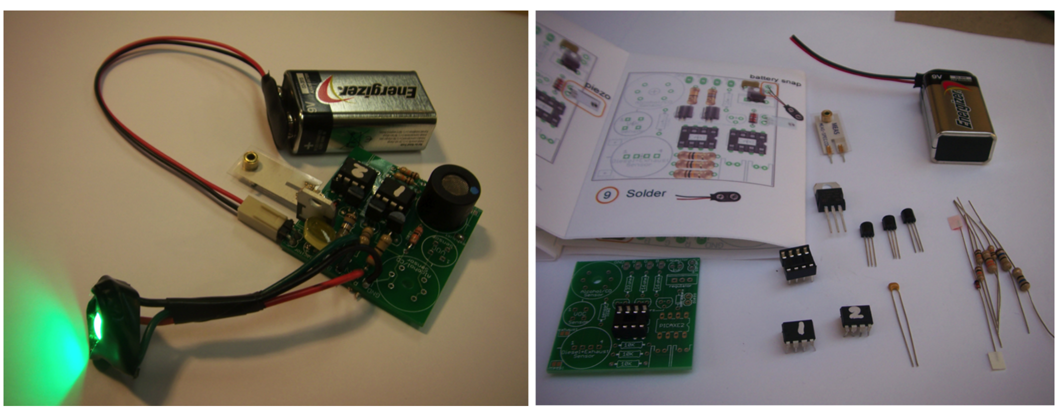

Figure 4.4. Air quality balloon kit: sensing board fully assembled and board, instruction booklet and all components.

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[23] NASA. New NASA Balloon Successfully Flight-Tested Over Antarctica, December 2009. www.nasa.gov

[24] NOAA National Weather Service. Radiosonde Observations. http://www.ua.nws.noaa.gov/

chronic respiratory illnesses, not to mention the pollutants' role in global climate change.

The circuit is powered by a rechargeable lithium polymer battery and relies on one of two inexpensive sensors from Figaro[25]: a VOC sensor or a dual function Diesel/Exhaust sensor (Fig. 4.4). The former measures either diesel or exhaust on separate balloons, and each balloon is labeled with the corresponding pollutant ('voc', 'diesel', or 'exhaust'). PICAXE, a low-cost ($1.50) microcontroller processes sensor data and controls a tri-colored LED. This LED is inserted into the balloon; the sensor, microcontroller and battery are mounted outside using wire and electrical tape. Balloons are illuminated based on surrounding air quality, glowing green, yellow or red to indicate low 'low', 'average', or 'high' pollution levels. Balloons are inflated using helium and their latex material naturally diffuses LED light, resulting in a large, evenly 'glowing', floating orb.

Our DIY balloon kit includes a custom circuit board that can be populated with a VOC or exhaust/diesel sensor. The former measures either diesel or exhaust on separate balloons, and one of two pairs of solder pads must 'shorted' (soldered across) to supply input from either the exhaust or the diesel pin of the sensor. The board is powered by a regular 9-volt battery or two rechargeable 3.3 volt polymer lithium ion batteries. The circuit relies on two PICAXE-8M chips (low-cost, $1.50 microcontrollers), with each sending pulse width modulation (pwm) to either a red, green, or both LED channels based on input from the sensor. The PCB also supports an optional piezo vibration sensor in order to alter balloon brightness based on movement (tug on the balloon string). A tri-colored LED resides inside the weather balloon, connected to the PCB board, which hangs below the balloon neck.

The board is intentionally designed for a non-expert to assemble, with ample spacing between through-hole solder pads and all components clearly labeled. In addition, a booklet with step-by-step picture instructions for assembling the board is included with the kit. Each DIY kit costs under $25 (VOC) or $35 (exhaust/diesel) and includes the PCB, instruction booklet and all components (including an air quality sensor, weather balloon, tri-colored LED, piezo, 2 pre-programmed PICAXE chips, battery, and resistors).

Ambient light thresholds

To support Do-It-Yourself (DIY) principles of easy access to materials and methods for creation by non-experts, we constrained the design of our system by choosing low-cost and low-fidelity sensors. We empirically determined our illumination thresholds (sensor values for green, yellow or red balloon lighting) by gathering sensor data around the city over the course of one week. We visited five

[25] Part numbers TGS-2201 and TGS-2620.

Figure 4.4. Balloon installation at a public street.

different neighborhoods and collected readings indoors, outdoors and at varying distances from busy streets, as well as in (traffic-free) parks. We used the observed variance in sensor output to determine thresholds below, within and above the average sensor output for green, yellow and red lighting respectively. Consequently, the balloons show air quality relative to the data collected in our city. Our display choice appropriately affords open interpretation through ambient lighting rather than exact numbers.

4.2.2 Public Installations

I selected two locations to install our air quality balloons: a public park and a city street (Fig. 4.4), expecting to see a range of balloon colors due to different amounts of traffic, people, etc. in the two spaces. Our installation coincided with extreme humidity (over 80%) and a PM2.5 (fine particulate matter) alert, causing many of the balloons to turn red. We inflated the balloons on site, tethering them to trees and benches (in public park) and on parking meters, cars and street signs along a city block. In addition to observing public interactions with our project we interviewed individuals who approached us and invited them to take some balloons. The installation was after dusk (around 9.30pm), so we encountered few people in the public park but numerous passersby approached us along the city block. We spent about one hour in each location.

Consistent with my framing of spectacle computing, nearly everyone who saw our installation was compelled to stop or slow down. In the public park and along the city block people expressed curiosity about the large, mysteriously glowing balloons. Most initial reactions suggested awe at the size and illumination: "*I thought there was a party down the street*", "*My kids love your balloons*", "*Awesome balloons*", *etc*. Most people understood the significance of the red-yellow-green lighting upon closer inspection—when they read the balloon labels, or after they asked us to confirm that the balloons 'showed air quality'. People reacted positively: "*Keep it* *up, I dig it!*", "*Diesel exhaust- that's a very bad thing*" or, "*Awesome, so how can we make money with this?*" Not surprisingly, individuals who lived in the neighborhoods where we placed our installations related more intimately, with one person commenting:

> This is my neighborhood and I know everybody, so I would probably put them [balloons] wherever I wanted. I think you should have more people with balloons…

Several people asked us if they could take a few balloons. One person excitedly pointed out:

> I think anything that's big and shiny will get America's attention… I know a little bit about VOCs so I can spread the word… Word, I feel powerful now, can she [friend] have one?

Thus, when first noticing the installation, passersby reacted with excitement and curiosity. Upon further reflection, however, stakeholders began to more critically discuss the visualization, the environment, and their neighborhood. Some further speculated on the role they can play in '*spreading the word'*.

4.2.3 DIY air quality balloon workshop

Working with a local DIY community in Pittsburgh, Pennsylvania, I also conducted a free air quality balloon-making workshop with 6 participants. The workshop began with brief discussion about attendees' backgrounds and motivations for participating. Each participant then chose one of VOC, exhaust or diesel balloon kits. Participants worked independently to assemble kits by following the included instructions, with the majority completing a board in about 30 minutes. Workshop authors then assisted participants in inflating balloons and attaching batteries to the PCB board (with tape). A few days later, an informal follow-up interview was conducted by phone or email to gather participants' feedback. Participants were compensated $15 for completing this interview. We recorded audio and photographed the workshop; we reference data owing to individual workshop participants as W1-6.

Participants

Our workshop was hosted by a local community that sponsors projects ranging from: creating hacky sack footbags by filling balloons with sand; to working with EL Wire; to "*yarn bombing and trying to incorporate social feedback and small bits of electronics into it*" (W6); or "*high altitude weather balloons to take pictures of the curvature of the earth*" (W1). Workshop participants (ages mid 20's to late 30's, 5 male, 1 female) have been involved with the DIY organization for various amounts of time: more than 2 years (W1); over a year (W2, W3, W6); 6 months (W4), and just under a month (W5). Participants' backgrounds varied, including degrees and work in design, engineering and English. Participants had some familiarity with soldering and different degrees of proficiencies with electronics—from relative beginner ("*other kits I've assembled were much simpler*", W6; "*my first introduction to soldering was the*

Figure 4.5. Air quality balloon workshop: soldering components onto the PCB and attaching sensor board to the balloon.

class that [DIY community] had in like September [6 months ago]", W4), to working on electronics projects on a weekly basis over the past few years (W1, W2, W3). None of the participants have previously worked with the PICAXE chip or Figaro air quality sensors. One participant owns a similar carbon monoxide sensor, but had not yet used it in a project.

Participants' motivations for attending the workshop

All participants indicated that they were drawn to the workshop for personal enjoyment: "a project that integrates balloons with technology is just kinda fun for us" W1; "I just thought it sounds like a really neat project" W3. Although participants were not environmental activists, some have previously thought about air quality in [city]. W5 was concerned with air and soil near his workplace:

> "I always kinda wonder about the soil- you know, like the lead… I wanna put this [balloon] at [work place] so people can see it as they drive over the [bridge name] bridge because it's got a lot of visibility." (W5)

Similarly, W2 noted, "I've just come to accept that [city] air quality sucks", while W3 was interested in sharing the project with his daughter:

> "I have a 3-year old and I'm really curious if it clicks… the concept of air pollution doesn't really mean much to her but I'm curious to see if see if with the colors it kinda clicks." (W4)

Assembling the DIY balloon kit

Most participants fully assembled their board in about 30 minutes, with only one participant taking over an hour due to a mal-functioning transistor (Fig. 4.5). Throughout the workshop, participants asked several questions about the hardware ("we'll want more information about the kit—just even like the components or the source code… just because it's kinda who we are, we like to explore things." W5,), as well as a few clarification questions about the instructions (*e.g.*, why are the steps in a certain order; or why/how to solder across the pads for the diesel/exhaust sensors). Participants were excited to turn on their balloons for the first time ("Testing the balloon! I felt like six [years old] all over again", W3;

"It was really fun to see the balloon light up for the first time, to see them all together in the dark at the shop", W6)

W4 also noted that unlike kits, which require programming after assembly, the balloon kit worked immediately:

> "The neat thing about this kit is you come out with a functional product. We were able to play with it immediately. It wasn't like… here's the product, now go write the software that does something cool." (W4)

Participants' experiences with balloons

After assembling the kits, participants were encouraged to interact with their balloons throughout the night as they saw fit (Fig. 4.6). Several participants took the balloons to a restaurant, but "it was really late and we couldn't figure out where we could take them where people would be" (W5). W4 brought his balloon home to show his daughter the following day:

> "She and I spent some time talking about it, I tried to explain it to her… I did the exhaust, so we did talk a little bit about the smoke that comes out of cars." (W4)

W3 tried to use long exposure photographs to capture his balloon changing color as he walked from a street intersection into the park (Fig. 4.6):

> "I walked from the intersection with traffic to the playground in the park to see how the colors would change. Also I figured it would make some cool pictures with long exposure…" (W3)

W2 discussed the project with his friends in India:

> "All of us agreed that it would be a great idea to have this at several locations thorough-out Bangalore. The air quality is noticeably different in different parts of the city and the weather forecasts give pollution readings only from a few places. " (W2)

Likewise, W5 hoped to initiate dialogue by sharing his images ("I'm hoping I can

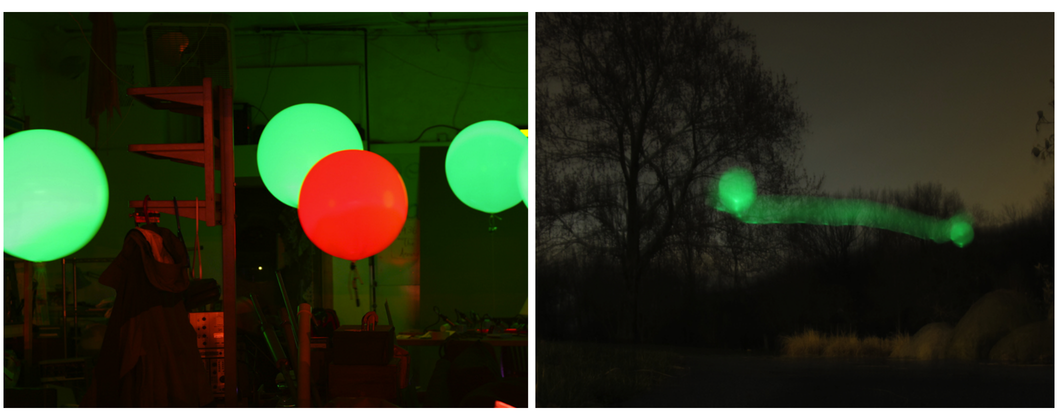

Figure 4.6. Fully-functional balloons built by workshop participants and participants' long exposure photo of balloon.

get some people responding on my Flickr pool… I think people would ask me what it's about", W5). W6, whose balloon deflated by the following afternoon speculated on using it for a whole day, "to see how and if it changed in the various places, and it would be fun to see people's reactions to it as well". Lastly, participants had numerous ideas for modifying the kit, from adding data logging ("so you could look back and see how things changed", W6), to incorporating the kit into a "semi-permanent system using plastic globes (lawn lights) on pipes" (W2). In summary, our workshop enabled 6 participants to assemble their own functional balloons, and interactions with the project led to exploration and speculation on expanding the project to include other functionality or be deployed in different regions.

4.2.4 Discussion

In this section, I presented the design of our air quality sensing circuit, which was mounted on weather balloons and distributed to stakeholders to visualize concentrations of VOC's, exhaust and diesel around our city. I detailed the deployments of this technology through public installations in city street and park and a workshop where 6 DIY hobbyists who were previously unfamiliar with the project and its underlying technology assembled functional balloons. The unconventional, vibrant, and public balloons served as entry points for environmental discourse among a diverse range of stakeholders. The installations and participants' experiences with balloons encouraged speculations about air quality between parents and children, local and international groups of friends, as well as complete strangers, either in person or by commenting on online repositories of images. These findings suggest opportunities to leverage spectacle computing for supporting new interactions between people, technology and space.

For instance, people with vested interests in a location (*e.g.*, homeowners) might prefer longer-term environmental spectacles in their neighborhood to facilitate local discourse, or community togetherness. Alternatively, individuals who traverse different parts of the city (runners or postal workers) might benefit from modular platforms (*e.g.*, Jeremijenko et al.'s Feral Robotic Dogs, 2009), which support spectacles and discussions across locations. Moreover, drawing from our workshop participants' willingness to modify the balloon kit (with data logging, or different form factors such as plastic globes), future systems can allow DIY modification and re-appropriation of the spectacle. Finally, the limitations of spectacles remain to be explored. When (if ever) do glowing balloons and other similar installations cease to be enticing? How can the effectiveness of spectacles be extended to inspire environmental discourse over longer periods of time?

Limitations

I intentionally chose low-cost sensors and pursued DIY methods in order to position this technology as a tool for bottom-up movements by ordinary citizens. Admittedly, this approach does not achieve precise air quality measurements, and our work faces the limitations of inexact and un-calibrated sensors. Our visualization appropriately represents sensor readings by illuminating balloons red, yellow or red based on whether the sensors read below, at, or above average values that were collected throughout the city. I believe there is tremendous value in communicating even these relative measurements of air quality to the public (as noted by one participant: "*I don't wanna read things like 'this is however many parts per million', I just want to say like 'this is bad, this is better"*).

4.3 Design Implications

I have thus far presented the materials and practices of individuals who extensively contribute to public spaces. I also detailed two tangible interaction approaches for authoring public spaces: the WallBot and the air quality balloon. I conclude with three implication areas that emerged from this work, focusing on how tangible media and spectacle computing can be used to broadcast matters of concern.

4.3.1 The importance of play

Both the WallBot research probe and the air quality balloon project inspired engagement by incorporating elements of play.

Playful DIY making

Given the importance of DIY for existing public art and activism practices, both of the technologies outlined in this chapter afforded customization and assembly from scratch. The transparent, DIY construction of the WallBot, for instance, led participants to discuss ways they would modify the robot to support their craft (*e.g.*, outfitting WallBots with light fixtures for light graffiti, or incorporating WallBots into street music performance). Likewise, the simple, clearly-labeled PCB board and step-by-step image instructions of the balloon project enabled non-expert users to create what they considered to be "functional products", emphasizing the "fun" of "seeing the balloon light up" or feeling "like 6 [years old] again". The DIY aspects of the balloon kit and the WallBot were playful, (*e.g.*, the balloon kit appealed to the local DIY community as a project that is "just kinda fun for us"). These insights suggest involving users in playful DIY making as an approach for inspiring public expression.

Future systems can support easy assembly and modification of the underlying technology to prompt ideas for creatively augmenting the project or speculations about broader issues such as air quality, as we saw in our workshop. New, even more flexible, easy-soldering or solderless kits that can be populated with a range of sensors might spur the interest of people outside technically-minded DIY communities. Alternatively, sensors with complex underlying circuits might support easy alteration of device appearance, display or form factor. A parallel body of research can explore intuitive instruction methods, including images, video or in-person demonstrations. More broadly, these approaches can serve to playfully engage everyday citizens in designing and building ubiquitous technologies project ideas into public spaces.

Playful media

In addition, the light-hearted and playful mediums (balloons and wall-crawling robots) engaged stakeholders with issues. The WallBot, through its whimsical ability to ascend metal surfaces, led artists and activists to reflect on deeper issues of anonymity, access, and authorship within their practices. Similarly, during our public installations of air quality balloons, observers began to think more deeply about pollution in their neighborhoods. Moreover, the balloons inspired participants to question and propose theories about air quality in their surroundings (*e.g.*, observing balloon colors between a park and a city street).

Whereas current applications tend to rely on participants' interest in the environment, community values or monetary compensation as motivations for sensing, an alternative body of work can encourage grassroots data collection through tangible and playful media. Future systems can explore incorporating play into the experience of environmental sensing. Balloons, for instance, can be used in range of new applications: balloons tethered to a map showing data for a region; balloons that visualize other environmental factors (*e.g.*, water quality); or large-scale projections that respond to onlookers' balloons. Likewise, the WallBot can serve as vehicle for air quality sensing across hard-to-reach spaces.

Moreover, other playful objects can be appropriated as sensors to support explorations of overlooked or hard-to-reach spaces (similar to Paulos, et al., 2014). For instance, air quality sensors embedded in kites can encourae engagement with and monitoring of air quality while playing on a beach; remote-controlled boats, outfitted with water quality sensors might inspire fun investigations of local water sources; or digging toys that include soil sensors could support interactive play with soil. Future applications may also leverage familiar platforms (*e.g.*, mobile phones) to distribute games and contests that motivate playful engagement with and reflection on the environment.

4.3.2 The power of spectacle

Both systems presented in this chapter—WallBots and air quality balloons—can be used to create spectacles. For instance, it was not uncommon to hear participants discuss ways WallBots could enhance and draw attention to public expressions, whether by interacting with audiences during street performances, communicating a political message, or by being construed as a piece of moving graffiti. Similarly, in the case of air quality balloons, our installations in public locations have attracted onlookers to approach the exhibit, ask questions, and voice their opinions. Participants who received working balloons actively sought attention by bringing balloons to busier streets and inviting strangers to photograph and discuss the project.

Unconventional, vibrant, and public media such as balloons and WallBots can create entry points for discourse among a diverse stakeholders, whether between street artists and the general public, or DIY makers and residents of local neighborhoods. The balloons, for example, served a boundary objects: they encouraged speculations about air quality between parents and children, local and international groups of friends, as well as complete strangers, either in person or by commenting on online repositories of images. These findings suggest opportunities to leverage spectacle computing for supporting new interactions between people, technology, and space.

For instance, people with vested interests in a location (*e.g.*, homeowners) might prefer longer-term environmental spectacles in their neighborhood to facilitate local discourse or community togetherness. Alternatively, individuals who traverse different parts of the city (runners or postal workers) might benefit from modular platforms (*e.g.*, WallBots or other kinetic platforms), which support spectacles and discussions across locations. Moreover, with DIY being an essential aspect of public expressions, and given our workshop participants' willingness to modify the balloon kit, future systems can allow DIY modification and re-appropriation of the spectacle. Finally, the limitations of spectacles remain to be explored. When (if ever) do glowing balloons, WallBots, and other similar installations cease to be enticing? How can the effectiveness of spectacles be extended to inspire scientific discourse over longer periods of time?

4.3.3 Tangible media as an instrument for projecting concerns

This chapter presented platforms that can be assembled and modified to make information—air quality data, graffiti, political messages, etc.—not only visible, but also compelling and hard to ignore. This suggests tangible media as a tool for sharing concerns and supporting grassroots initiatives. On one hand, other new and unexpected media may effectively entice and empower bottom-up data collection: paper airplanes, remote-control cars, dog collars, tree leaves or roller skates, to name a few, might serve as novel vehicles for environmental sensing (similar to street sweepers or pigeons). Data collected by such distributed means might be aggregated into more traditional representations (*e.g.*, maps, graphs) to serve as political artifacts.

Alternatively, tangible media might enable users to project data within and across urban spaces in more playful and unconventional ways. Wireless communication between visualizations (*e.g.*, balloons, WallBots) and sensors can support spectacles that are physically removed from the locations being sensed. Users could place vibrant artifacts in remote spaces to draw the attention of activist communities, policy makers, or the general public to local issues.

4.6 Conclusion

This chapter explored the tools and mechanisms for public expression. I began by detailing a study of individuals who extensively contribute to public spaces through street art, performance, and activism. This study relied on WallBots as a research probe, revealing DIY materials, authorship, anonymity, and appropriation of space as key elements of grassroots public expression practice. Drawing on these findings, I then introduced air quality balloons, a DIY kit for vibrantly projecting environmental data in public spaces. Installations in city streets and park, and a workshop where participants assembled their own, fully functional sensing balloons resulted in a range of dialogues around local air quality issues. These findings highlighted, the importance of play as a public engagement strategy—both through the making process and in terms of the materials used (wall-crawling robots, balloons). Moreover, I have argued for spectacle computing as a valuable strategy from projecting information, ideas, and messages into the public sphere. Complimentary to recent trends in invisible and seamless computing, this approach uses tangible and vibrant media to overtly bring matters of concern to the forefront.

5 Nurturing natural sensors

The last two chapters broadly explored ways to express matters of concern. Focusing on place-based community sensing and vibrant, DIY spectacles as two complimentary strategies for drawing attention to issues, I have shown how these approaches can support communities to coalesce around shared issues. Moving forward, this chapter inquires more deeply into the practices of local knowledge production amongst such emerging groups. Specifically, I present the practices of individuals who routinely rely on organic materials and living systems to infer information about the environment and gather knowledge about local ecosystems[26]. An extensive field study with gardeners, beekeepers, zoologists and other 'experts' in the domain of organic and non-digital sensing is used to reflect on the question, when is an electronic sensor appropriate or necessary in a given context?

Within HCI, the majority of citizen science systems support local data collection via digital means (*e.g.*, digital sensors, mobile phones, online visualizations). Indeed, while a sensor can be broadly defined as any device that responds to a physical stimulus, the majority of HCI research has understandably focused on electronic instantiations of sensing devices. This chapter serves to challenge the traditional HCI concept of sensing as being purely electronic. I present a field study of 10 participants who routinely work with living organisms such as plants, fish, reptiles or bees and draw on hybrid information channels—from organic, to analog, and digital—as forms of environmental monitoring. While many people make inferences about the environment (e.g., a cloudy sky suggests the possibility of rain), this sample of participants is expected to be more attuned to environmental processes as their work explicitly engages with living systems.

Visionary research has often turned to groups outside 'mainstream' user populations to productively inform new areas of inquiry within HCI. For example, Chetty et al. (2008) and Dillahunt et al. (2009) both study home resource consumption to draw out implications for the design of ubiquitous energy sensing; and Wyche et al. (2009) examine how Pentecostals use communication technologies, suggesting interventions for supporting alternative value systems in UbiComp. Likewise, the study presented in this chapter considers fringe 'sensing' practices by reporting on participants' use of digital devices, traditional tools, and living organisms to infer environmental conditions and inform actions related to local ecosystems (Fig. 5.1). In doing so, the work reflects on current sensing

[26] Parts of this chapter were previously published (Kuznetsov et al., 2011).

Figure 5.1. Everyday biomarkers: bee behavior reflecting local weather and bloom cycles (top left); scale larvae signifying a pest problem (top right); fish appearance indicating water quality and parasite levels (bottom left); reptile posture suggesting a disturbance to the environment (bottom left).

paradigms in ubiquitous computing through the lens of organic and non-electronic sensing. The findings offer new insights into everyday biomarkers and serve to expand HCI's visions of sensing to include more traditional instruments as well as the living organisms themselves. I conclude with three opportunity areas to help critically frame future work in ubiquitous sensing: (1) leveraging non-digital sensors, (2) designing technologies that teach new ways of 'seeing', and (3) enriching practices of data collection and sharing.

5.1 Methods

We conducted semi-structured interviews (2-3 hours) with 10 participants who work with organic organisms (plants, reptiles, bees, fish, etc.) in and around a mid-sized city in the United States. Participants (ages 20's to late 60's; 3 female, 7 male) were recruited through local gardening and beekeeping communities, and the city zoo. Interviews took place at participants' respective sites of work (garden, zoo, apiary, etc.) to support rich, in situ reflections. We asked participants to walk through their daily routines (with regards to gardening, beekeeping, etc.) and, in doing so, show us their tools and local settings. Additionally, open-ended questions probed common uses of digital and non-digital sensors (and other technologies, such as computers, mobile phones, etc.); participants' knowledge of the environment based on tools and living systems; and how this information is shared with fellow practitioners or other stakeholders.

We audio recorded all interviews and took field notes, documentary photographs and select videos. The research team repeatedly reviewed the audio and all field materials to draw out underlying themes. Interview audio recordings were transcribed and coded using these themes. We also created conceptual models and affinity diagrams to reveal themes and unexpected connections across our data.

5.2 Findings

I begin by introducing the participants. I then detail our data in regards to: 1) monitoring practices— participants' use of technology, tools and observation to monitor the environment; 2) types of living indicators— how participants use living organisms as environmental indicators; 3) collection, sharing and speculation— patterns of discussion and speculation around biomarker data.

5.2.1 Participants

We recruited 10 diverse participants who routinely work with living organisms, including: beekeepers who maintain hives at home and throughout the city as a part of local community initiatives; an Integrated Pest Management (IPM) scientist who controls pest populations in a tropical greenhouse through organic means, such as beneficial insects that consume pests; a horticulturist who innovates, builds and maintains bioshelters (self-sustaining greenhouses, "designed on the model of a cell- like a living cell that looks like a living organism", H); organic farmers and gardeners who work independently or with urban agriculture groups; and reptile and fish overseers at a local zoo that acutely examine animal behaviors to inform their daily work. We reference data owing to individuals from each domain as follows:

· Organic farming, urban agriculture group [F1, F2, F3]

· Organic gardening, independent [G]

· IPM (integrated/organic pest management), city zoo [I]

· Beekeeping, urban beekeeping community [B1, B2]

· Horticulture, independent [H]

· Aquarium and fish keeping, city zoo [A]

· Reptile keeping, city zoo [R]

Participants' backgrounds

All participants have worked in their domain for several years, and most have been involved for decades: 8 participants have lived on farms or worked in gardens, zoos or aquariums for over 20 years. 7 participants earned professional degrees in biology, sustainable community development, etymology, zoology or a related field. However, all participants emphasize learning their craft through a mentor ("*Beekeeping is kind of an art or a craft, you really do need a mentor... you really need somebody local that can really tune you in with what's going on locally*", B1) or hands-on experience ("*just a function of working with fish a really long long time—you start to get kind of a zen feel for, ok something is not right there*", A).

Motivations

Participants rely on their work for income, either by selling equipment or produce, through education initiatives (radio shows, books, etc.), or employment at an urban agriculture community or the city zoo. However, they also emphasize enjoyment ("*I enjoy growing- personally that's the most rewarding thing for me*", F1; "the fact of seeing something go from just a little ity bity thing all the way to fruition", G) and the broader benefits of their practice ("*every third bite of food that we eat as a society is attributed to the honey bee*", B1) as primary motivations behind their work.

5.2.2 Monitoring practices

Despite differences in their specific domains, all participants' work revolves around regular check-ups to track the health of the organisms their work relates to. From daily 'rounds' at tanks and aquariums ("*The first thing we do when we start is to check on our animals, we do rounds*", R; "*You just stand and watch them [fish] for a little bit and you see... Am I noticing anything that's off*", A) to weekly inspections of select plants ("*Every Wednesday we go and inspect certain plants*", I) or the bi-weekly examination of beehives ("*I check my hives once in 12 to 14 days*", B2), participants routinely monitor their environment. I continue by detailing participants' monitoring practices, organized by technological complexity, starting with practices that rely on technology as a primary means of data collection, and ending with practices that draw on more traditional instruments or do not involve any tools ('naked' human observation).

5.2.3 Technology-mediated monitoring

Predictably, some monitoring practices fundamentally rely on technology. Digital sensors are used routinely, occasionally (to clarify an anomaly), or early on (before participants acquire a skill and abandon the technology).

Figure 5.2. Technologies used by participants: ORP probe, routinely used to monitor ozone levels in aquariums, refractometer, occasionally used to check honey before harvesting; thermometer, checked daily.

Routine digital sensing

Participants draw on certain technologies on a regular basis. A thermometer is used twice a day in aquariums ("*if you can catch the temperature before the chiller has been off for too long maybe you can save the animals*", A); daily at greenhouses, reptile tanks and bioshelter ("*if it's cold [we] build the fire and open and close vents as needed*", H), and weekly in IPM:

> We try to look at the temperature and humidity and see how that affects the population of pests… we know that certain insects like spider mites, they love hot dry temperature. (I)

Weather is also checked regularly (online, TV, etc.), for instance, to infer soil conditions ("we're always looking at the weather, like you shouldn't do this when the ground is wet, you should do this", F2) or availability of pollen:

> I watch to see what the weather is like: the flowers may be open, but maybe raining and the plant flowers can't secrete nectar, the bees can't get to the flowers, maybe too cold maybe very dry, there's not an excess moisture for the flowers to secret a lot of nectar. (B1)

Moreover, A checks ORP sensors twice a day to ensure proper function of the ozone generator ("*check in's and check out's. Spend a good hour and a half of my day*", A) and runs water quality tests weekly ("*we do monitor it [water] once a week to make sure the carbon is still removing the chlorine*", A). R uses a scale to weigh reptiles while they are quarantined ("*we do weights, measurements, we want to make sure the animal is thriving in quarantine*", F). F1, F2 and F3 take annual soil tests as part of their farming community's standards but do not notice drastic differences as most soil is imported compost ("*the nutrients would change a little bit, your nitrogen would jump up and down cause plants use too much of it*", F1).

Occasional digital sensing

In addition to the digital tools employed during routine monitoring, some technologies are used only occasionally, to clarify an anomaly or confirm an observation. For example, although G does not routinely test the soil, he would use a test if his plants were not growing properly:

> I've never tested the soil here, I'm getting everything I want out of my garden so I'm not gonna worry about it. It's more if you're having problems… if your beets aren't heading up, you know probably a pH problem or a nutrient deficiency [test the soil to] figure out what it is. (G)

Similarly, when F1 noticed dust accumulating from nearby dump trucks, he sent a sample to a local lab for testing:

> The biggest air quality concern is the dump trucks full of slag that drive by… there's this like black dust that collects in the street and we scooped some of that up recently and sent it away for testing. I'm curious to see… (F1)

The aquarist participant relies on water quality testing when he notices unusual fish behavior ("*we just start checking everything to see where's the problem, what's wrong*", A). Water quality sensors include a pH meter, a spectrophotometer, which can run up to "*400 different chemical analysis*", and a dissolved oxygen meter:

> We have a dissolved oxygen meter in the lab, we don't go around and check all the exhibits once a week… if there's a problem… we'll bring the DO [dissolved oxygen] meter out. We'll check that it's not too low or too high. (A)

Likewise, before harvesting honey, B2 occasionally uses a handheld refractometer to check its water content ("*anything above 18% tends to ferment, anything below 18% doesn't ferment*", B2). Thus, while technologies such as a DO meter or refractometer are not part of routine practice, participants tend to draw on them when their observations suggest ambiguous outcomes.

Abandoned digital sensing

Lastly, in several instances, digital sensing is used early on but is eventually abandoned. F2 no longer uses a sprinkler timer since it caused a pipe to "burst", and participant I does not trust the Fogstat system to correctly water the greenhouse due to faulty humidity sensing ("*it hasn't been calibrated in a while so it's way off*", I). Additionally, some sensors were abandoned when a participant acquired a certain skill. For instance, participant I stopped testing her soil when she learned to infer soil quality from plant growth:

> I used to [test soil] every year but it kept coming back pretty much the same. I guess I'm just sort of working off how everything looks- everything seems to be green and growing pretty well. (I)

Our findings thus suggest that while some technologies are regularly or occasionally used to monitor the environment, several types of sensors have been abandoned either due to malfunction or lack of useful data once a skill was acquired.

5.2.4 Traditional tools and observation-based monitoring

We discovered that a wide range of participants' monitoring practices do not involve digital sensing to understand environmental processes and states.

Participants rely equally (although in different ways) on naturally occurring phenomena and non-digital 'measurement' tools.

Magnification and counting tools

Participants routinely use counting and magnification tools to infer environmental conditions. In beekeeping, a “monitoring tray”—a tray imprinted with a square inch grid—is placed under a hive (Fig. 5.3). B2 accesses the infestation by counting the number of mites (pests) fallen on each square:

> This is a monitoring tray… I'll slide it in there [under a hive]... We can either do a 24-hour count or a 15 min count. I just do a 15 min count. I'd look at it, and go ok there's 6 [mites] in that one and on average there's 5 or 6 mites, which is heavy per square… So then I can determine whether I want to do a treatment. (B2)

Similarly, F2 uses handmade traps (notecards covered with a sticky substance) to monitor pests based on the amount of caught insects:

> To see them [pest insects], we set sticky traps… you can go and you stick them in the dirt and you can go and see what you have… I don't count them [insects], but I kinda look at it. Like what's been caught on these cards-[F2 looks at card] it's not a ton, but it's definitely a lot. (F2)

In IPM, a magnifying hand lens helps observe larvae stages on leaves to determine if beneficial insects are thriving:

> If you look at this [larvae] under a hand lens, it has a really white wooly covering to it… getting to know the larval stages helps recognize that your beneficial insect is getting established. (I)

Likewise, high-resolution magnification is used to monitor fish and reptiles. A microscope is used for annual checkups (“*the vet department will look at it [fecal matter] under a microscope and look for various parasites*”, R), or inspections of fish, often cross-referenced with “*pictures of different parasites*”:

> We'll open up the gill cover take a little snip of the filament put that on the slide with the skin scrape look at it on the scope look for things that are crawling around. (A)

Participants thus regularly use magnification and counting tools to reveal information that is invisible to the naked eye.

Monitoring through physical engagement and action

In another set of practices aimed at exploring information that is not accessible through passive observation (hearing, sight, etc.), participants become active

Figure 5.3. Magnification and counting tools: monitoring tray; hand lens; handmade sticky trap.

agents in their environment. For instance, the whitefly pest tends to reside on leaves and is not easily discernable to the naked eye. To access this infestation F2 habitually taps her plants, causing noticeable clouds of whitefly to emerge ("*they [whitefly] come off in like a big cloud when you run your hand over it [plant]",* F2). Similarly, since nectar is not visible from outside the hive, B1 and B2 routinely 'tip' each beehive to gauge its weight and infer whether the amount of nectar is sufficient:

> You just pick up—you tip the hive. You pick up one end and you can tell by the weight how many stored pounds of honey there is in the hive and that's something we do this time of the year to see if the bees are starving. (B1)

In the bioshelter, H uses his finger to track moisture at various soil depths, accessing 'data' that might be unreliable or inaccessible through other means:

> The human skin is a lot more sensitive than the gauges [moisture sensors]. When you want to know how moist the soil is at the bottom of the pot or the top of the pot... stick your finger in the pot and you know how far down it is. (H)

Our aquarist participant shares an analogous practice, scuba diving into exhibits to monitor aspects of fish appearance and behavior that might be invisible from outside the tank:

> I would love to be in my exhibits more… when I go scuba diving I can get this close to the animal, I can see a lot more. Because of the way the windows filter the light and the animals react to the light and everything... there are things you just miss that if you get in you can see. (A)

These and other examples across all of our studied practices suggest physical action (tapping, tipping, inserting, etc.) as a means of gathering richer information, inaccessible through 'naked' and passive observation.

Monitoring through 'naked' observation

Finally, participants regularly infer information about the environment through 'naked' observations. Our findings include examples of the use of all five senses: smell ("*if the water is really bad you can actually smell the ammonia",* A); sight ("*parsnip starts to sprout so that usually means the soil gets to 70 degrees… by [seeing] what's germinating I can tell the temperature*", H); taste ("*some old time beekeepers… can taste that droplet of nectar and identify the flower that way, based on the taste*", B1); hearing ("*red belly woodpecker calling that's when a lot of my spring stuff is going [to be planted]… he's not gonna start mating calls till the weather is—till the light is in a certain way*", G); and touch ("*soft scale [pest]… exude a sugary substance called honeydew, so it's kind of a way of finding them—when a lot of leaves are getting sticky*", I). These instances illustrate how the human senses alone serve to inform participants of a range of processes and factors in the environment.

5.2.5 Types of everyday biomarkers

All 10 participants shared numerous experiences and habits of inferring environmental factors by observing elements of living systems. The everyday biomarkers used by participants can be classified as showing one specific factor (one-to-one); several possible factors (one-to-many); or the status of the ecosystem as a whole (ecosystem).

One to one

Biomarkers in this category map to concrete phenomena: a "*chicken coop smell*" in a beehive is used to detect foulbrood—a deadly bacterial infestation (B2); green water in a fish tank suggests an ozone deficiency ("*I can look at this water and tell that the ozone system hasn't been working for 2 weeks on this… because it's green*", A); particles resembling 'saw dust' at the bottom of vine plants help identify a squash vine borer pest (F1); hydrangea color (pink or blue) is matched with low or high soil pH (I); a piping sound signals "*that a [new] queen is getting ready to emerge*" and a colony will soon split (B1); accentuated leaf growth in fruit plants is correlated with "*too much nitrogen in the soil"* (F2). Input from these and a multitude of other one-to-one biomarkers is nearly always mapped to a single cause and a subsequent associated practice.

One-to-many

One-to-many biomarkers inform participants of several possible factors as opposed to one conclusive state. For instance, interveinal chlorosis, a yellowing between veins of leaves, suggests nutrient deficiency or pH imbalance ("*a lot of times pH effects the availability of nutrients*", I); blossom end rot in tomatoes is "*caused by a lack of calcium"* (F1), or "*the calcium's there but the plant isn't able to accept it because of the moisture content*" (G); a 'sliming' fish suggests poor water quality or a parasite:

> If a fish is sliming really heavily that's a good sign that something's wrong. It could be- water quality and the slime is trying to protect the animal [or] if there's a parasite that's causing the fish to slime really heavily to push that parasite off. (A)

Similarly, bees returning to the hive trembling indicate a contamination, but do not imply one specific chemical:

> If you have bees that are flying normally and coming back and trembling and dying they've obviously either got sprayed by something or got contaminated... (B2)

Thus, one-to-many biomarkers typically lead to further reflection and investigation on behalf of our participants in order to infer the cause or actions that should follow.

Ecosystem

Lastly, participants rely on numerous biomarkers to learn about the ecosystem as a whole. For example, B1 infers local drought and blooming cycles by observing his bees:

> One of the neat things about beekeeping is that it kinda gets you in touch with your local ecosystem. When there's a drought I can tell, the bees aren't bringing in much nectar, you can tell when the bees are bringing in pollen by observing the hive so you know when the first flowers are blooming in the spring, you can tell what flowers they're working based on the color of the pollen. (B1)

Similarly, our IPM participant monitors the greenhouse by tracking the balance between pest and beneficial insects:

> You always want to reach a balance, you never want to totally eradicate an insect… If you wanna sustain a population of beneficial insects, you always wanna have a baseline or a lower level of the pest insect - because they'll keep your beneficial [insect] around. (I)

Alternatively, organisms are also used to infer problems in the ecosystem: coral reef bleaching as "*a response to stress, it's not necessarily any specific stress*", (A); algae on reefs suggesting "*a disturbance to the system… nutrients are very tightly cycled, algae indicates that they're not so tightly cycled*", (A); the endangerment of the Philippine crocodile, suggesting "*pollution, habitat loss, people kill them out of fear*", (R); or diseases prevailing on unhealthy plants ("*when a plant is stressed, a whole host of things can then be multiplied, diseases.. and pests will spread more easily*", F2). These examples illustrate how biomarkers are used to learn about complex processes within the ecosystem or infer information about the ecosystem as a whole.

5.2.6 Data collection, sharing and speculation

Participants maintain a variety of records of their practice (Fig. 5.4) including: daily logs of water quality and feedings (A, R); an extensive log and computer database of pest infestations (I); recipes of honey products (B1, B2); schedules and layouts for crop rotations (F1, F2, F3); or a gardening journal that combines planting information with mementos from personal life ("*I'm hoping that my grandkids and great grandkids will be able to read that stuff*", G). While G was hesitant to share his journal due to an interweaving of sentimental material with garden data, all other participants were eager to show us their records. However, in practice, they rarely saw value in sharing everyday data with people outside their work ("*the only time that we really drew these graphs and all is when we were doing a PowerPoint doing a talk about the program*", I; "*what I do every day I don't think should be on the report- cleaning and feeding and the sort of mundane things*", R). Records thus serve to inform aspects of the work (*e.g.*, where to plant crops, what chemicals to add to the water), but are not typically shown to others.

Sharing Mechanisms

Nevertheless, participants do routinely share aspects of their work. Day to day information is discussed with other community members by word of mouth ("people call me... I lend out an extractor to people and they come and pick it up and they tell me what's going on", B1; "casual conversation", F1). More serious concerns, *e.g.* a mosquito spraying, might be posted to community listserves:

> The mosquito spraying for instance, we put out a big email blast that said hey this is happening we're gonna monitor our hives, we suggest you do the same and we will let you know if anything came up we just kept everybody updated, we said nothings happening, nothings happening and everybody else reported the same... and it's good, watch out for each other. (B2)

Twitter and Facebook are utilized to broadcast community events ("tweet about things like—we're delivering this and this to the restaurant", F2); while media such as books, blogs and radio shows offer gardening information and advice to the general public (G, H). Alternatively, R speaks directly to zoo visitors to correct misunderstandings:

> I'm always listening in on people when they talk and I try to interject with the correct information in a way that I don't insult them… maybe tell them more about the animal they didn't know and try to make them understand. (R)

Participants thus rely on a range of media, from conversation to Twitter and mailing lists, to share aspects of their practice in and outside of their communities.

Speculation

Participants tend to actively discuss the implications and causes of unusual environmental phenomena. For instance, all farming participants commented on a recent stinkbug infestation that affected the east coast of the United States. F2 wondered if it was caused by weather patterns and discussed the matter with other farmers:

> I think there's something in the weather pattern that allowed them [stink bugs] to reproduce at those rates… a lot of farmers we spoke to had whole crops that were destroyed and that was very strange because we've never even seem the attack food crops. (F2)

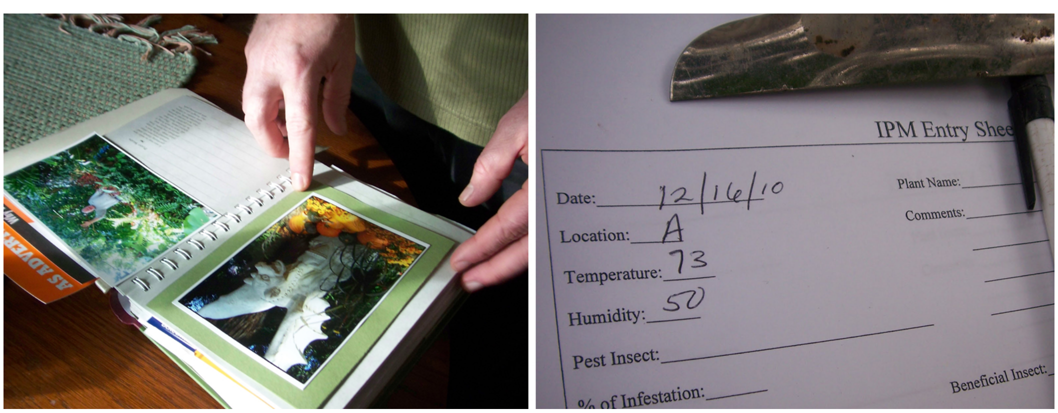

Figure 5.4. Participants' records: gardening journal and IPM data entry sheet.

Consequently, numerous community members began to experiment and share possible solutions to the problem:

> I got them on my blog—this woman sent me a picture [of] a mouse going onto her deck and eating stink bugs… then another woman called me… she gathered all the stinkbugs that she found and threw them out on the deck and here come the turkeys eating the stinkbugs. This is really great news, because to this point we didn't know if local birds would eat stinkbugs and now they're discovering it. (G)

Likewise, urban water quality emerged as an issue of concern for many participants: G prefers to water his plants with rainwater ("*just because there's no chlorine in it, fluoride and all that other crap*", G), H uses a private well, and city water is filtered prior to entering A's aquariums. In particular, A notes the lack of accessible information about urban water ("*you can call them and ask, or you can just test it*", A), noting that certain chemicals are lethal for fish:

> They [the city] can change the chemicals they use for disinfection [of water]… now a lot of facilities are switching to chloramine… so if it gets into your fish tank it really wreaks havoc. (A)

Moreover, the rise in colony collapse disorder—a national die-off in honeybees—has spurred a debate on pesticide use in beekeeping communities, locally and internationally. B2 showed us numerous posts on an online international forum (*e.g.*, "*document shows EPA allows bee toxic pesticide despite their own scientists' red flags*", B2), suggesting pesticides and genetically modified plants as likely causes:

> …all these self pollinating plants, or synthetically modified plants they don't need pollinators anymore, so that's taking away a food source, on top of that they're spraying the shit with chemicals that's killing the bees. (B2)

Both B1 and B2 also blame lack of government regulation ("*In Europe they banned neonicotinoids because they believe it is hurting the bee population, but in this country, they haven't been able to prove it's a problem, but a lot of beekeepers think it is a problem*", B1). Similarly, G speculates that commercial advertisements promoting stylized images of green lawns led people to use chemical sprays on their yards, resulting in nitrogen soil deficiencies ("*clover takes the nitrogen out of the air and puts it in the soil… it wasn't until advertisers told us that we don't want clover in our lawns that were taught not to have clover in our lawns*", G). To counter such advertisements, G endorses organic practices on his blog, radio show and in numerous publications: "*this is what I teach people- there is no reason to use any chemical in your garden*" (G).

Likewise, R is also taking action in his field— collaborating with another zoo to breed and reintroduce the endangered Louisiana Pine Snake into the wild. He notes the broader processes, which may have contributed to the endangerment:

> They [Louisiana Pine Snakes] feed primarily on… the pocket gopher, and when it went they went with it, and the reason the pocket gopher went is cause they specialize in certain types of grass—a lightening would burn an area where these things would grow—the grass would

> grow first... well with forest management now there is no burning… that's what started the problems (R)

The above instances illustrate a range of reflections based on ambiguous or unexpected inputs from living systems. The resulting speculations are often projected to broader groups to infer potential meaning(s) as well as to consider (and in some cases even organize) collective action aimed at the responsible or intervening social and political forces.

5.3 Discussion

I presented findings that detail the practices of 10 individuals who directly and indirectly work with living organisms on a daily basis. I highlighted participants' proficiency with and access to a range of technologies, which range from social media such as mailing lists, blogs, forums and Twitter, to digital information systems such as a database of records or online weather reports, to highly technical sensors for soil and water quality. While the participants skillfully draw on these digital technologies throughout their practice, they also habitually rely on living systems (biomarkers) to infer information about the environment and shape their course of action. Below, I outline two unique themes that emerge from participants' use of everyday biomarkers.

5.3.1 Biomarker systems

The findings suggest that biomarkers are perceived to be and used as integral components of larger systems. Some practices revolve around systems that are purely organic: designing a bioshelter "*on the model of a living cell*", or using one-to-many and ecosystem biomarkers (fish appearance, bee behavior, balance between pest and beneficial insects, *etc.*) to infer complex processes within an ecosystem, or gain a glimpse into its well-being as a whole. Other practices confirm or clarify 'naked' perceptions of living organisms with data from analog and digital tools, resulting in systems of interdependencies between technological and biological inputs. More broadly, participants' collective practices reveal larger, socio-political systems that shape their work: regional water quality treatment, national policies to preserve or destroy snake habitats, or international regulations on pesticide use.

5.3.2 Active engagement with context

Biomarkers not only cue participants to environmental states, but also serve as points of engagement with underlying contexts. In the most direct sense, participants physically interact with the environment. When tapping on plant leaves, tipping a beehive, inserting a finger into the soil, or diving into an aquarium, participants are active and immersed in their surroundings. On a higher level, participants become involved in the social and political processes that shape their practices. Examples such as beekeepers debating EPA regulations on international forums, farmers experimenting with natural remedies for stinkbugs, a gardener advising the general public against using commercially advertised chemical sprays, and a reptile keeper collaborating across state lines to preserve endangered snakes, all suggest that biomarkers serve to inspire active participation in broader contexts.

5.4 Design opportunities

I conclude with three design implications emerging from the data. This section serves to expand the HCI community's conceptualization of 'sensor' and present new opportunity areas for the design of future sensing systems.

5.4.1 Leveraging non-digital inputs

Previously, I outlined several popular categories of sensing in HCI research, whereby a sensor is typically conceptualized and studied as an electronic device. My work suggests examples of both traditional tools (hand lens, etc.) and living organisms that may be construed as 'sensors'. Our participants effectively monitor factors such as soil temperature ("*by seeing what's germinating*"), ammonia levels (by smelling the water), amount of stored honey (by tipping the hive), or pest infestation levels (through counting and magnification tools) without the use of soil sensors, water quality monitors or IR insect tracking. When participants do rely on digital sensing, they often employ such technologies only as a secondary measure (*e.g.*, chemical analysis of water when fish do not appear healthy; testing the soil if plants are not growing properly).

As new research emerges to question technology-focused approaches in HCI (*e.g.*, "could technology be replaced by an equally viable low-tech or non-technological approach?", Baumer et al., 2007), and their implications (*e.g.*, sustainable disposal of digital artifacts, Blevis, 2007), I argue for expanding the HCI community's vision of sensing beyond electronic devices, to include living organisms and traditional tools.

Our fieldwork shows that sensors (digital, analog or organic) are rarely if ever used in isolation. Instead, participants fluidly navigate across a hybrid system of biomarkers, traditional tools and digital devices to gain insights into environmental processes and inform future actions. These findings suggest an opportunity to shift from designing sensing technologies to designing ubiquitous systems that incorporate living organisms and traditional tools along with digital devices. In particular, this paradigm could open a rich design space for active participatory sensing or passive environmental monitoring, for instance by expanding prior work in public air quality sensing to integrate inputs from plants and insects, or monitoring water quality (*e.g.*, Kim et al., 2011) based on fish activity. Alternatively, entirely new ubiquitous systems could emerge to broaden our understanding of the ecosystem as a whole (rather than specific aspects such as water or air quality) by integrating inputs from plants, insects and animals along with analog tools and digital sensors into holistic representations of the environment. For instance, a system might track the well-being of a neighborhood by visualizing noise, air and water quality along with insect activity and appearance of street plants.

5.4.2 Designing technologies that teach new ways of seeing

Our data suggests that over time, participants developed a "zen feel" for the complex processes in their environment. Occasionally, highly skilled and nuanced ways of "reading" biomarkers were accompanied by the use of more advanced technologies. However, such technologies were sometimes abandoned after participants developed a skill (*e.g.*, "*working off how everything looks*" instead of testing the soil), or were used infrequently and only to help resolve a problem that more traditional tools could not (*e.g.*, D.O. meter to verify water quality when fish appear sick). These findings suggest a new model for designing digital sensors: sensing technologies as tools that support new ways of 'seeing' or engaging with the environment. Such sensors move away from 'smart' technology and towards systems that encourage human awareness of and reflection on about the natural world.

Embracing low-fidelity signals

Digital sensing tools can offer remarkable degrees of precision, and the collected data lends itself to powerful methods of analysis. Graphs, charts and other scientific presentations are common throughout HCI sensing applications ranging from activity recognition to input sensing. These approaches contrast with the numerous 'imprecise' sensing practices of our participants: biomarkers (plant growth, reptile activity levels, etc.) and more traditional tools (*e.g.*, monitoring tray) often provided highly useful and reliable information without the degrees of precision characteristic of digital sensors. Imprecision often prompted our participants' physical involvement with the materials being sensed: tipping a beehive, inserting a finger into soil, or tapping a plant leaf. These and similar actions can inspire future input techniques to support indiscreet and fluid interactions with digital systems. More broadly, ubiquitous systems can draw on 'imprecise' digital sensing to embrace "*ambiguity as a resource for design*" (Gaver et al. 2003) or "*design for doubt*" (Paulos, 2009). For instance, as an alternative to providing concrete measurements such as time and duration of electrical appliance use (Gupta et al., 2010), activity recognition systems might explore imprecise sensing to facilitate more critical explorations of human behavior. Similarly, research supporting outdoor learning experiences (*e.g.*, Rogers et al.,

2004) might use imprecise sensing to encourage inquiry into ambiguously represented environmental phenomena.

Peripheral engagement

The use of imprecise biomarkers and tools also inspired participants' engagement with context that is peripheral to the phenomena being sensed: by looking at larval stages, the IPM participant assessed the "balance" and well-being of the entire greenhouse; by tracking bee behavior, a beekeeper became "*in touch with [the] local ecosystem*"; by observing algae on a reef, A inferred a "*disturbance to the system*". While often subtle to articulate, this type of engagement seemed to play essential roles in developing a sensibility for understanding the environment. In addition, peripheral engagement was at times suggested as a source of meaning. Whether by directly "*seeing something go from just a little ity bity thing all the way to fruition*" or taking pride in the fact that "*every third bite of food is attributed to the honey bee*", participants drew experiential value from their practice.

These findings highlight the importance of the degree to which a digital sensor either facilitates or hinders peripheral engagement. For example, as noted in a recent CHI panel on food and sustainability (Hirsch et al., 2010), a system that senses soil moisture and waters plants remotely may discourage active presence in the garden. Consequently, the user may neglect or never learn important cues about the health of plants.

However, digital sensing also has the potential to support new and exciting forms of peripheral engagement, especially with phenomena that are difficult or impossible to sense with 'naked' human perception. For example, water quality sensing systems used in infrastructure and environmental sensing (*e.g.*, Froehlich et al., 2009) can reveal relationships between the home water system and local water source. Similarly, air quality monitoring can connect users with processes that contribute to air pollution in the home or neighborhood. On a higher level, considering peripheral engagement in the design of sensing systems can support more holistic interactions, including engagement with broader phenomena aside from ones directly being sensed.

Scaffolding

Through "*years of experience*" and insights from mentors, our participants developed highly nuanced sensibilities to infer information such as complex air or water quality from cues as subtle as a sliming fish or a trembling bee. With some participants viewing their practice as "*an art or a craft*", our findings suggest opportunities for new scaffolding tools that train individuals and groups to 'sense' better and differently. For instance, a body of research in activity recognition and participatory sensing appropriates mobile phones as digital sensing devices. Complimentary to this work, mobile phones and other ubiquitous platforms can be used to direct people to their local environments, providing information that supports 'reading' natural or artificial biomarkers, such as appearances of plants and behaviors of animals. Some information technologies can serve as scaffolding tools that are needed less frequently or not at all after a sufficient level of skill has been developed. Others can be designed to nurture mentor/apprentice relationships in communities, encouraging sensing as a "*conjoint practice*" and tool for community togetherness (DiSalvo et al., 2009).

5.4.3 Enriching practices of data collection and sharing

Our participants routinely record environmental data in logs, databases, and personal journals. While these documents are not directly shown to other stakeholders, the participants actively share aspects of their practice, from day-to-day events discussed with local practitioners through "causal conversation", or telling zoo visitors "more about the animal", to broadcasting issues of local concern on community listserves and speculating about large-scale phenomena on international forums. These practices reveal opportunities for collecting and sharing inputs from living systems and analog tools as well as digital sensors.

On one hand, existing and future citizen science applications can incorporate a new user group: individuals working with living systems. Technologies can combine routine information collected by beekeepers, aquarists, reptile keepers, or gardeners with rich forms of metadata, for example: augmenting mite counts with observations of bee behavior; supplementing water quality data with images of fish appearance; integrating gardening data with mementos from personal life; or more broadly correlating inputs from organic systems with users' insights into the surrounding environmental processes. Alternatively, metadata might be embedded into the organic materials themselves (similar to augmenting fabric with storytelling, Rosner et al., 2008). For instance, a beehive could be annotated with current flower conditions or weather patterns; a plant bed might show crop rotation history, *etc.*

On a higher level, data collected from living organisms, coupled with personal or group annotations, can serve to further issues of community concern and political interest. Consistent with research that encourages collective action around shared issues (DiSalvo et al., 2009), there are opportunities for supporting activism around the well-being of living systems (similar to technologies that sustain 'publics'). For example, local beekeepers could capture and share videos of bee flights, attributing metadata to draw attention to potential pesticide spraying in the area (as per Campbell et al., 2008). Similarly, gardeners and aquarists might upload images of fish and plants to track possible changes in urban water quality. Moreover, using the scaffolding tools outlined earlier, everyday citizens could be involved in the collection and sharing of biomarker data. Examples include mobile applications that enable photographs and annotations of nature reserves to assess snake habitats, or insect counting tools to track local pest populations. Resulting data could be shared within and across communities of local residents, individuals working with living systems, or government officials thus supporting "*politics of scale*" (Dourish, 2010) by linking people through their collective actions in the service of broader social change.

5.5 Conclusion

I presented the environmental monitoring practices of 10 individuals who routinely engage with living organisms. These participants draw on independent and interrelated systems of biomarkers, traditional tools and digital sensors to infer information about the environment and inform actions related to local ecosystems. These findings were used to reflect on current sensing paradigms and explore approaches for incorporating living organisms, traditional tools and digital devices into future sensing systems. I proposed (1) leveraging non-digital inputs in ubiquitous systems, (2) designing technologies that teach new ways of 'seeing', and (3) enriching practices of data collection and sharing as opportunities for expanding and guiding future research in this area. Ultimately, this work presents a broader framing of and a more hybrid approach towards sensing infrastructures that support the diversity and richness of local knowledge production.

6 Hybrid materials and systems

In the previous chapter, I discussed how communities of expert practitioners draw upon a range of materials and systems to produce local knowledge. In particular, I highlighted how living organisms and analog tools offer rich insights into environmental phenomena, enabling stakeholders to engage with and reflect on the world in ways that digital devices often fall short of supporting. This chapter builds on these ideas by presenting the design and deployment of two hybrid systems that incorporate analog and organic materials along with digital technologies to support *new ways of seeing* the environment[27].

As non-experts and scientists alike continue to rely on digital technologies to measure and quantify the world around us, to what extent does digital sensing *limit* our understanding of, reflection on, and attunement to the environment?

Figure 6.1. Bio-electronic soil sensing device deployed at an environmental outreach community center.

[27] Parts of this chapter were previously published (Kuznetsov et al., 2014; Kuznetsov et al., 2013).

Digital technologies, undoubtedly, allow us to efficiently collect and analyze environmental data, often with remarkable degrees of precision. However, these conventional sensors and visualizations (graphs, charts, etc.) also create a layer of abstraction between digital representations and the underlying physical phenomena. For instance, air quality—a fundamental component of human life and health, as well as a cornerstone for local and global ecosystems—is often represented as a heatmap or number in HCI visualizations (*e.g.*, Willet et al., 2010; Kim et al., 2010; Burke et al., 2006; and others). The reduction of rich physical phenomena into discrete digital representations has been shown to narrow focus and potentially disengage users from broader context (Brynjarsdottir et al., 2012; Froehlich et al., 2010). Moreover, this approach often enforces a single, "totalizing and universal" point of view (Bardzell, 2010), leaving little room for dialogue between stakeholders, values, and concerns. This chapter explores pluralist interaction design across two novel systems: a low-tech, paper-based approach for visualizing particulate pollution, and a bio-electronic system that monitors microbial activity in soil.

The first half of this chapter details an ultra low-cost method for collecting particulate samples across entire neighborhoods, cities, or geographic regions. The data, which includes images of the actual air pollution particles, supports rich reflections on aspects of air pollution that are often less transparent with digital technologies: sizes and types of particles, causes of pollution, and local and temporal trends. The assembly of heterogeneous materials—paper products, a microscope, and the air particles themselves—supports new forms of engagement with the sensing process and surrounding context. I then shift focus towards a different type of hybridity: a system that visualizes bacterial activity inside *Winogradsky columns* (Fig. 6.1). Winogradsky columns incubate soil samples over the course of several weeks, culturing naturally occurring microorganisms as they process the metals and nutrients in the soil (Rogers, 2004). I developed a system that visualizes bacterial activity in the columns by measuring soil conductivity and the voltage potential (energy) generated.

Both the paper-based and the bio-electronic systems were deployed in workshops with urban communities, enabling participants to reflect on particulate pollution and soil microbiology respectively. Insights into individual and collective appropriations of hybrid systems reveal design trajectories that build on emergent themes in HCI: new perspectives on materiality, which arise from integrating organic and paper materials with the digital; a reframing of time, as systems shift from providing instant feedback to supporting prolonged engagement; and an emphasis on new ways of seeing that expand beyond individual behavior change. I conclude this chapter with design implications for (1) integrating digital and organic materials; (2) prolonged engagement with systems; (3) new ways of seeing; and (4) ethical considerations.

6.1 A low-tech sensing system for particulate pollution

This section aims to bridge the "physical-digital divide" (Blanchette, 2011) between sensors and the phenomena being sensed through the design of a low-tech, paper-based approach for visualizing particulate pollution. As part of this system, participants collect air quality samples with particulate matter traps that cost less than $1 and are easily assembled from common paper materials (Figure 6.2). Unlike many digital devices, these traps are not much thicker than paper, and do not require a power source. The collected samples are returned to central community locations, where participants can view, count, and reflect on the particulates in their air using high-precision microscopes. High-resolution images of the particles could then be shared with broader audiences online, via mobile phones, or public displays.

This DIY system thereby separates environmental sensing into two steps: low-tech sample collection, and high-tech sample analysis. This approach is radically different from many existing solutions, where environmental samples are collected and analyzed by a single sensing device. Thus, while many existing sensing systems are relatively low-cost, they still face the challenge of scaling to larger participant groups by necessitating users to have access to specific devices (*e.g.*, smart phones or other sensing platforms), or possessing technical skills (*e.g.*, basic electronics knowledge). Furthermore, our visualization approach (high-end magnification) removes a layer of abstraction by enabling participants to see the physical pollutants in their air.

6.1.1 DIY paper-based sensing system

Motivation

Particulate matter (PM) consists of coarse particles (2.5-10 microns) that result from tire and asphalt wear, pollen, or dust, and fine particles (2.5 microns and

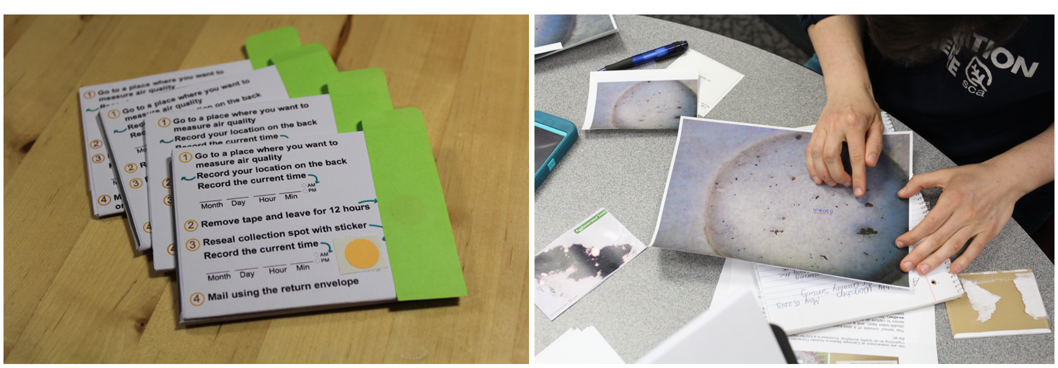

Figure 6.2. Particulate matter traps, ready to be mailed to participants, and participant examining microscope image of collected particles during community workshop.

below), emitted by industrial or vehicular combustion, as well as the recombination of sulfur dioxide, nitrogen dioxide, and volatile organic compounds (EPA, 2014). Particulate pollution has been linked to increased risk of respiratory illness, cardiovascular disease, and shorter life expectancy, not to mention the pollutants' role in global climate change (Pope, 2009). PM continues to affect urban air quality, especially in our city, where air quality has been rated as among the worst in the U.S.

PM can be monitored with commercial sensors, such as the ones used to determine the daily Air Quality Index (AQI) (Mintz, 2009). However, these measurements are interpolated across a large region and do not show variations between streets or neighborhoods. Though several sensors, such as the Dylos Air Quality Monitor ($300), have been developed for PM sensing on a consumer-level, these devices represent air quality as the total number of particles per unit of air, without reporting particle size, type or origin. Our approach makes sensing more transparent by enabling communities to view the physical particulates in their air on a local scale.

Paper computing

Our sensing tool, which can be assembled from common paper materials, draws inspiration from paper computing (Buechley et al., 2009). Paper computing is a growing area of research within the tangible interaction community, focusing on the integration of paper materials into computations artifacts. For instance, a recent TEI workshop by Rosner, *et. al* combined traditional bookbinding practice with new building techniques and electronics (Rosner et al., 2011). littleBits is an open source kit that integrates digital components with materials such as paper and cardboard (Bdeir, 2009). Likewise, Eletronic Popables is an interactive book comprised of craft materials along with conductive paints, sensors and microcontrollers (Qi et al., 2010). The system I present below applies paper computing concepts to the domain of citizen science.

Sensing procedure

We developed a sensing system and procedure that can be run by local groups without the aid of 'experts' in the field. To organize particulate pollution monitoring within a specific region, an activist community would first download a set of freely-available instructions and purchase paper materials (Fig. 6.3) from a stationary or office supply store. Volunteers would then assemble many particulate matter traps (details below) and mail these via regular postal service to residents in a local neighborhood or entire city. Recipients would 'deploy' the sensors for a fixed amount of time to collect air samples in a location of their choice. The sensors could then be mailed or brought back to the community center. Community members can analyze the samples using a microscope, and/or organize a workshop whereby participants could view the samples they collected.

Particulate pollution data, which might consist of high-resolution images of particulates, as well as particle counts and relevant metadata, could then be assembled into a public database or visualization. With the cost of each particulate trap being under 1$ (including return shipping), this system could be implemented across a large scale. In addition to being assembled in bulk by the organizing community, the particulate sensors could also be put together by individuals and returned to a community center. Though the cost of a microscope may be upwards of $80, the organizing community needs to only purchase a single device, which could then be shared by different groups to process hundreds or thousands of samples.

Design process and pilot deployment

With this sensing procedure in mind, we explored several particulate trap designs. Our initial ideas were inspired by O'Reilly's Air Pollution Testing Lab (Thompson, 2012), whereby microscope slides are covered with petroleum jelly, exposed to air fixed amounts of time, then sealed in shallow bowls, and later observed through a microscope. We wanted to iterate on this approach such that i) the materials need not be obtained from specialty science stores; ii) the traps could be shipped using regular mail without contaminating the collected samples; and iii) the assembly process could be pipelined by community volunteers.

Using paper and acrylic as a base, we experimented with several sticky materials to collect particles, including tape and Vaseline. We also considered the tradeoffs between longer and shorter exposure times: shorter deployments might not collect enough particles to show local variations; deployments of several hours might interfere with participants' schedules; and longer deployment (over 12 hours) might face weather challenges (rain, snow, etc.). After testing different instantiations of the sensor throughout our city for varying amounts of time (from 15 minutes to 24 hours), we decided on an initial design consisting of note-cards, clear tape, several stickers (for sealing the sample), and an exposure time of 2 hours.

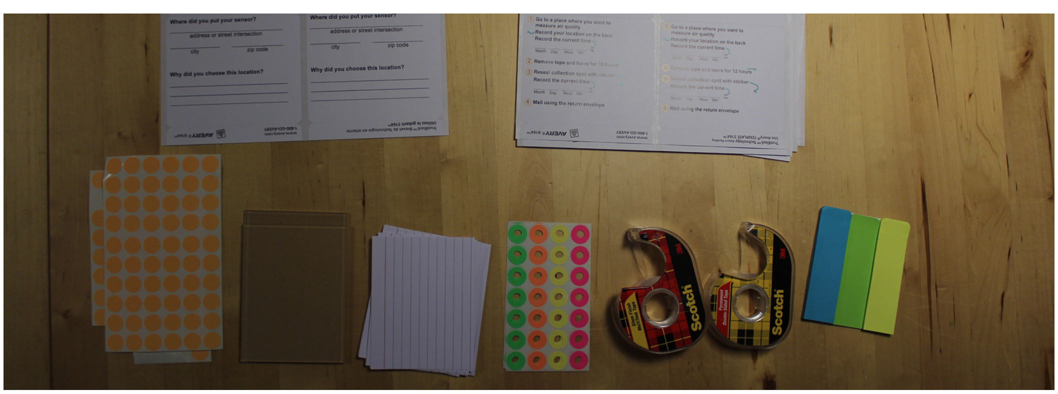

Figure 6.3. Materials needed to assemble a particulate trap.

To evaluate this design, we organized a pilot deployment with an air quality activist group. Particulate matter traps were mailed to 13 volunteers, who used the sensors and sent them back to us. During an optional workshop, which was attended by 3 people, participants provided feedback on sensor design, as well as viewing the collected particles. Based on this early feedback, we increased the exposure time to 12 hours to capture more variability between samples, and changed the visual design to highlight the spot where particulates were being collected on the sensor.

Particulate pollution trap

Our final sensor (Fig. 6.4) consists of 5 index cards, trimmed to 3”x4”, and taped together. A single hole-punch across the cards serves as the collection spot. One side of the hole is covered with clear scotch tape, with the sticky side facing into the hole to collect particles. A paper reinforcement is adhered around the hole on the opposite side to visually highlight the where the sample is being collected, as well as to create more space between the collection surface and the stickers used to seal and reseal it. A removable sticker is placed over the reinforcement, covering the collection spot to prevent particles from accumulating before the sensor is deployed. This label has a non-adhesive tab, such that it can be easily peeled off to begin particle collection.

Instructions, which consist of 4 simple steps to use the sensor, are printed on an adhesive address label and attached to the front. The sensor is then attached to a .2” thick acrylic rectangle to make the trap more stable (*e.g.*, prevent it from being flipped by wind). Another label on the back of the sensor prompts users to record their deployment location. The sensor can fit into a medium sized (3.625” x 5.125”) envelope with a return address, which in turn can fit into a regular-size envelope addressed to recipients. Users can place the sensor in a location of their choice and peel the removable label from the collection spot. The sensor is resealed with another sticker (provided in the envelope) 12 hours later, and returned to a processing location via USPS.

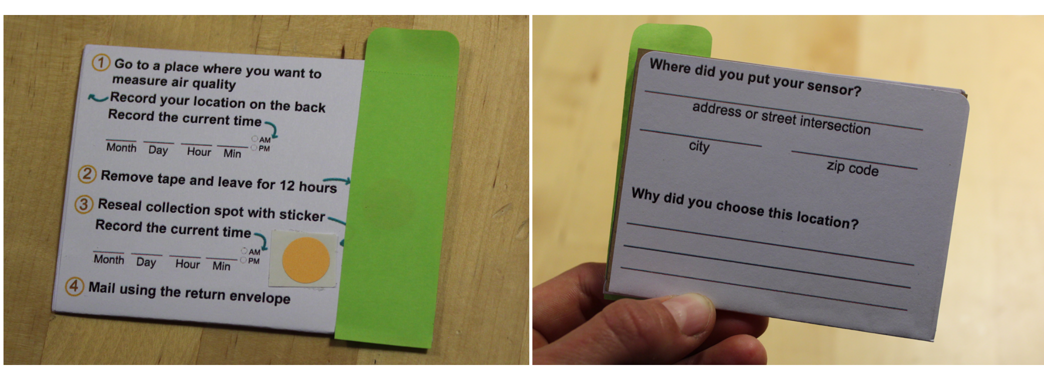

Figure 6.4. Sensor front and back.

Viewing the particles

Samples can be viewed with a magnification device (digital or analog microscope, or a simple magnifying glass). For our proof-of-concept deployment, we chose to use a Venus USB 2.0 microscope with 200x magnification, which showed particles of 10 microns or larger. We designed a custom 3-D printed microscope stand to add stability while viewing the samples. A future system might interface the magnification device directly with a public visualization such as a map overlay of the particulate images.

6.1.2 Deployment

Our system was evaluated through a deployment with GASP, a local air quality activist group. This community, which has been active for over 50 years, works on public engagement, remediation, and policy-level initiatives to improve air quality in our region. We consider this group to be early adopters of new sensing methods, and a good representative of the type of group that might adopt our sensing system on a city-wide scale. An announcement was sent to the community mailing list, inviting volunteers to use our particulate sensor and attend a workshop whereby they could view and analyze the particles in their samples. Similar to our earlier, pilot deployment, a particulate matter trap was mailed to each participant. Recipients used the sensors in locations of their choice and returned them to our workshop by mail or in person.

Community workshop

In preparation for the workshop, we created 12 cards with high-resolution microscope images of particles and their descriptions from Microlab Gallery (2013). Focusing on particles that are more common in urban areas, our cards included agglomerated soot, grass and tree pollens, coal dust, concrete dust, road dust, slime mold, tire wear, and weld debris, among others. During the workshop, participants used a microscope to view and measure the particles collected by their sensors. Images from each sensor were printed, and participants could use our information cards to help identify particles in their samples. The printouts were then assembled onto a physical (paper) map of our city based on where each sample was collected (Fig. 6.5). In addition, participants learned how to create sensors from scratch and were invited to take them home with them. After the workshop, we conducted informal phone interviews (20-40 minutes) with participants to gather feedback. Data from the workshop and interviews was audio recorded, transcribed, and coded to themes, and serves as the basis for the findings reported below.

6.1.3 Findings

We recruited 8 participants (3 male, 5 female; ages mid 20's to late 60's), with varying degrees of involvement in the organization: two people work closely with the group as staff and board members, while others attend group events, and/or check the mailing list and website for news and updates. All participants stated that they have been interested in air quality prior to our study, with 5 people checking the AQI on a regular basis. However, only one person, the community staff member, has used a handheld monitor to measure air quality before.

Participants' motivations

Participants cited different reasons for getting involved in our project, ranging from pure curiosity to specific air quality concerns such as pollution from traffic, industry or construction. Most people used the sensor near their homes, except for P7, who used it in his office at work. To varying degrees, all participants expressed a similar motivation for their sensor placement—to monitor the air they are most often exposed to. As P5 explained, "I put it on a windowsill at my house. It's the air I breathe".

However, within their broad interest in surrounding air quality, participants also expressed unique concerns about specific causal factors. P2 noticed "that last few years that my car just gets coated with these fine particles during the day [near her home]" and wanted to monitor diesel truck pollution, which she thought to be the cause; P3 was concerned about emissions from coal processing plants in the area, which she associated with a 'sulfur smell' she sometimes felt in the morning; and P4 was worried about nearby construction:

> That location is very close to where they're working on construction so it's of concern to me, to my house… Also I found it to be interesting that there's a hospital right there, so I thought it would be interesting to see what the area is like around the hospital. [P4]

Above, P4 notes that she placed her sensor close to a construction site that might be impacting air quality near her home as well as at a nearby hospital. To summarize, participants shared a general interest in air quality prior to our project, and wanted to use our sensors to track different factors contributing to air pollution.

Ease of assembly and ease of use

To evaluate our design, we intentionally mailed the particulate sensors without any additional instructions, beyond the four steps printed on the sensor itself. All participants reported that the sensors were 'standalone', 'straightforward', or

Figure 6.5. Air quality workshop: measuring and counting particles; particle information cards; participant's microscope data.

'really easy' to use, and no one expressed difficulty or confusion regarding the sensing procedure. All of the used sensors (5 returned by mail) were properly sealed, with deployment times and locations filled out by participants. Moreover, participants reported that the length of deployment (12 hours) easily fit their schedules, with 7 people leaving their sensor in the morning and resealing it in the evening, and one person leaving it out overnight.

Likewise, participants reported that assembling the sensors from scratch during our workshop was also easy ("It actually pretty easy to put this together, so it would be fairly easy to do," P1; "I thought it was easy." P5; etc.). Participants, unprompted, discussed the potential for mass-producing these tools through conveyer belt style assembly:

> I could see mass producing them, having people do you know a 100 of them a night or maybe even 200 or 300 because they're not that difficult, and then more people cutting the index cards and getting things to size as opposed to putting them together. [P2]

Above, P2 suggests that the steps required for assembling particulate traps could be split between people, and the process could be streamlined. To summarize, all participants agreed that using and assembling the particulate sensors, as we designed them, was easy.

Seeing air quality

Throughout our workshop and during follow-up interviews, participants reflected on how our system enabled them to see air quality differently. Below, we report on three themes from our findings: seeing different types of pollution; seeing local and temporal variations; and transparency—seeing the workings of the sensing system itself.

Types of air pollution. Our system enabled participants to see the sizes, colors and textures of the particles in their air. This led participants to reflect on the physical composition of the samples collected by their sensors. For instance:

> Well I guess I learned more about what's actually in the air in that spot and the examples on the table, those were very nice to compare to, and I just thought that it was soot and exhaust and things like that, things that could be affecting the air quality. [P5]

Above, P5 describes how he compared his air quality sample with the particle information cards at the workshop, and speculates that soot and exhaust might be present in his air. This type of comment—which highlights being able to see what's in the air—was common across most of the participants. For instance, P4 suggested that our sensing system can be used to see "what is in the air, is it pollen or dust or smoke, I mean how to break down whatever topic we're interested". Likewise, P1 noted that through the microscope, he "could look at different kinds of pollution and how they'd show up".

Being able to see the particles collected by other people's sensors at the workshop also led participants to reflect on, and sometimes learn new information about the causes of pollution. For example, P2 noted that she tended to associate particulate pollution with coal plants and was surprised to see another participants' high particle content near a street:

> It's interesting that hers had a really high content cause it was more on street level so it showed me at least that… I never thought much about the diesel as much as I thought about the coal plants and the air pollution. [P2]

In this excerpt, P2 notes that seeing particles from another location prompted her to think about a different type of pollution (diesel).

Local and temporal variations. Participants also discussed how our sensing system might reveal variations in air quality between different streets and neighborhoods, as well as across different times of the day/week. They emphasized being able to see results from "my neighborhood" or "my location" as opposed to the general AQI interpolated for the entire city. For example, below P3 explains that although the Environmental Protection Agency (EPA) air quality monitors are not far from where she lives, these measurements may still fail to capture the way pollution moves through the region and affects her home:

> I'm interested in air quality and ways to monitor my own air pollution here in my home… even though I'm not on the other side of the river where the [EPA] monitors are… and that's where the coal emissions are and they go in different ways depending on the valley. [P3]

Other participants wanted to use the system to track the movement of polluted air across the region:

> Normally, with the EPA website, it's a kind of broad monitoring of the air so I'd be curious to see if it's worse near Clairton, where it's a major source of pollution in the county. [P5]

> When we talk about the air kind of moving it comes west to east and we get all of Ohio's pollution, so I'm wondering if it comes up or if it's coming up… So I would like to see lots of people doing it [using the system] at higher elevations to see if there's a difference in the air vs. below that. [P2]

In the excerpts above, P2 and P5 suggest using our system in a nearby township that is considered be a source of pollution, as well as across different elevations within our city. Here participants are highlighting the value of seeing local variations that are not captured by EPA monitoring. Similarly, P2 also suggests tracking air quality patterns over time:

> If I could do it [collect samples] 7 days in a row, 24 hours a day, and I could detect patterns to see something different on some days, it would be more beneficial for me to be able to see that as opposed to what the general number is saying. I know that it would be my block as opposed to the entire county. [P2]

Above, P2 envisions using our system to detect air pollution variations over the course of a week.

Transparency. Lastly, several participants commented on the transparency of the sensing system. Below, P4 compares our sensing procedure with her previous experience of measuring pollution with a handheld monitor:

> Once again I think the other monitors are giving good readings and accurate reading, but it doesn't have that extra affirmation where you can see it for yourself. With the air monitors you can't see what it's taking in and why it's giving you the reading it's giving you um so the wonderful thing about this project is you can see that. [P4]

Here, P4 notes that unlike other 'black-box' sensing devices, our system shows how the air sample is being collected and visualized. This 'affirmation' enables users to see not only the pollutants in the air, but the workings of the sensing system itself. To summarize, this section highlighted how participants were able to see air quality differently through the use of our system: by seeing the physical particulates and the local and temporal variations in pollution, as well as seeing the process by which the samples were collected and visualized.

Sharing sensing tools and data

Seven of the participants said they would share the project with their family and friends, and several said they would send the sensors they made during the workshop to other people. Participants envisioned a digital (online) version of our paper map to show particulate images and counts to a bigger audience and discussed several ways that the system could have broader impact.

Education and awareness. First and foremost, participants saw our approach as an educational and outreach tool for both adults and children. For instance, participants suggested deploying the system in areas with poor air quality to make residents more aware of air pollution:

> It's definitely worth continuing, especially giving it to people who don't think much about air pollution. [P2]

> [use the system] to make aware and educate Pittsburgh'ers about the fact that our air isn't of the best quality. You get so used to it unless you go out of state. [P3]

These excerpts represent examples of how participants discussed the system as an awareness tool for the general public. Moreover, several people also suggested working with local schools to deploy the system with children:

> It would be a great project for kids to take home and then take a look at it on the computer screen, these small tiny particles that just- that's in the air is what's on that. [P2]

P2's suggestion—to use our system to show children particulates in their air—was not unique. Others, especially P4 and P3, emphasized the project as a 'marvelous teaching tool' or a 'great visual' for younger audiences, who might be less engaged with numeric data such as the AQI.

Action. In addition to raising awareness, participants emphasized that the system could serve to change public behavior towards alleviating air quality problems.

> It's not just like a number. There's different things that are in the air, and there's different situations that positively or negatively effect these types of pollutants. You can kinda get people thinking about things they can do, on days that are worse. [P5]

Here, P5 discusses how visualizing air quality by showing the particles present, as opposed to a single number, might result in public actions serve to reduce specific pollutants. Similarly, P1 notes that the system could show her how she personally contributes to the pollution in the area and help change her commute:

> I think being able to visualize [air quality] would really help me with my commute and how I would be contributing to the pollution in the area. [P1]

Data validity. Two of the participants highlighted a limitation of our system: the particulate matter visualization is not calibrated to readings from a high-precision sensor. The particle counts conducted during the workshop, therefore, do not directly correlate to professional data. As P3 pointed out, the data from our system may not be convincing to the health department or city officials:

> You can't take this information to the environmental protection department because it's not from an official monitor. [P3]

In summary, this section outlined some of the broader implications of our system as discussed by participants: as an education and awareness tool or an approach for influencing behavior. However, the system also has limitations, as the data is not calibrated against high-precision measurements.

6.1.4 Discussion

So far, I presented the design and deployment of our low-tech, paper-based sensing system. Our deployment is limited in that it involved a relatively small number of environmentally-oriented individuals. Our system is intended to scale to large numbers of people as an approach for raising air quality awareness. Our deployment offers insights into how a community of activists might appropriate this tool. Furthermore, while in its current form, the processing of particulate data is labor-intensive—it involves inspecting each sample under a microscope—in the future, this process could be automated and particle counts could be conducted using vision techniques. Below, I discuss the trade-offs between low-tech and high-tech sensing, and I more broadly reflect on the hybridity of this system and the interactions it afforded at the end of the chapter.

Low-tech vs. high-tech sensing

The sensing system I presented was intentionally designed as an ultra low-cost, scalable approach for monitoring air quality. As was confirmed during our workshop, the particulate traps can be easily assembled by people with no prior experience, and the assembly could be streamlined to create the sensors in bulk by a small number of volunteers. The sensors, which consist of widely-available paper materials, can be sent to large groups of stakeholders. These sensors are easy to use, and samples collected by thousands of people can be processed with a single microscope at a community location. The resulting data—images and counts of particulates—can show relative variations in air quality and serve to engage a wide audience, including children, in issues of air quality.

However, as some of our participants pointed out, this data is not calibrated against precise measurements such as parts per million (ppm). Although the use of low-cost/low-precision sensors is common throughout participatory sensing research (*e.g.*, Aoki et al., 2010; Campbell et al., 2006; Kim et al. 2010), this approach has limitations. Data that shows relative rather than absolute (*e.g.*, ppm) pollution levels may not serve as a convincing tool to lobby government officials, or be indicative of specific health effects. The big challenge for participatory sensing research is therefore to balance issues of affordability, scale, and precision.

While it is not feasible to send professional-level sensors to residents of a whole city, or expect people with varying degrees of expertise to know how to use these, future tangible interaction systems may take on a more hybrid approach. High-precision sensors could be coupled with low-resolution inputs and outputs. For instance, thousands of low-cost sensors such as the ones we designed might be deployed in conjunction with a few high-precision devices. The paper-based sensors can enable citizens to collect and compare samples around their homes, raising general awareness. Upon learning about air quality through this easily accessible system, citizens might then come together and use data from a professional device to initiate dialogues with policy makers. Alternatively, low-precision crowd-sourced data might be calibrated against readings from a high-precision device. Interactive or tangible visualizations might then show how data collected by everyday citizens correlates with scientific measurements such as the AQI.

6.2 Community engagements with living sensing systems

I have thus far discussed how our hybrid approach for air quality monitoring affords new interactions and challenges, from the trade-offs between scale and precision, to the experiential opportunities of being able to *see* the air pollution. I now shift towards a different type of hybridity: the intersection between organic and digital, explored through the design of a soil monitoring system. This bio-electronic assembly is inspired by my earlier study of biomarkers (Chapter 5), as well as the many projects that incorporate organic and living materials as inputs and outputs into '*bio-electronic hybrids*'. Examples of the existing hybrids include

OpenPCR[28], an open source tool for performing Polymerase Chain Reaction—mass replication of DNA for gene testing outside of professional laboratories; *I/O Plant* which enables designers to manipulate plants through sensors and actuators (Kuribayashi, 2007); *Botanicus Interacticus*, a system that supports expressive interactions with plants (Poupyrev et al., 2012); and 'virus energy generators' (Krotz, 2012). These new trends begin to raise questions for the HCI community. What are the implications, challenges, and opportunities for HCI research when living organisms are incorporated into environmental sensing systems?

At the very least, the integration of living and digital systems offers new insights into many emergent themes in HCI: the (often) slower biological timescale speaks to a body of literature on Slow Technology (Hallnäs, 2001); the uncertainty of living processes might serve as a point of reflection on ambiguity in design (Gaver, 2003); the nuances of sustaining and supporting life might result in new forms of community engagement and participation (Bardzell, 2010); the de-emphasis on technology itself can be treated as parallel to sustainability work considering 'low tech' and 'no tech' solutions (Brynjarsdottir, 2012). I explore these ideas by introducing a hybrid, bio-electronic soil sensing system.

6.2.1 Designing a bio-electronic system

Motivation

Soil plays a key role in plant growth, animal populations, water quality, and multitude of other factors that influence not only our food supply and health, but also the wellbeing of local and global ecosystems. Pittsburgh, Pennsylvania in the United States, where this research was conducted, has a storied environmental past, making soil of particular concern. Coal and iron mining dominated the area's landscape over the past century, resulting in heavy dumping of slag—silica and metal compounds. Despite numerous clean-up efforts, the region still houses evidence of the environmental damage (Tarr, 2005).

Soil pollution affects local farming and gardening communities. Prior work in our city revealed a range of public concerns around pollution and mineral deficiencies that inhibit plant growth, lead to pest infestations, and in some cases, render produce unfit for consumption. Prior soil sensing research focused on distributed sensor networks to support agriculture (Beckwith, 2004; Hwang, 2010; Pearce, 2010). Complimentary to this work, I explore a visualization of Winogradsky columns to foster community engagement with soil.

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[28] http://openpcr.org

Winogradsky columns

Designed by and named after Sergei Winogradsky, a scientist deemed "father of microbiology" (Dworkin, 2012) the Winogradsky column illustrates the versatility of soil microbes. At the bottom of the column, soil is combined with a sulfur source (*e.g.*, gypsum), carbon source (*e.g.*, newspaper), and calcium (*e.g.,* eggshells). The remainder is filled with a mixture of soil and water. The column is made of a transparent material (glass, plastic, *etc.*) to support photosynthetic reactions, and capped to limit oxygen supply. The microorganisms at the bottom are thus deprived of oxygen while being supplied with sulfur compounds and natural light. Over the course of a month or longer, bacterial colonies will grow and transform soil compounds, resulting in color gradients throughout the column.

During the incubation period, anaerobic bacteria at the bottom of the column catalyze reduction reactions and produce hydrogen sulfide. This byproduct moves up the column and becomes oxidized by the aerobic bacteria in the top layer, forming sulfate (Rogan, 2005). Electrons are thus continuously passed from compound to compound and between bacterial groups. This movement is reflected by changes in soil conductivity and could be harnessed as a microbial fuel cell. In addition to illustrating the sulfur cycle, Winogradsky columns are a powerful tool for exploring the biodiversity of soil microorganisms and the range of nutrients and metals present (Madigan, 2000). I chose to focus on the Winogradky columns because they 1) are low-cost and relatively easy to assemble using household components; 2) form a conventional/'tried-and-true' approach to holistically viewing soil quality; and 3) offer a natural juncture for many of the bio-electronic themes we discussed (slowness, hybrid materials, *etc.*).

System design and implementation

Goals. From early on, we envisioned a system that would enable community members to observe and coalesce around bioactivity in their soil. Our goal was to create an unobtrusive system that lives and is lived with for long periods of time as it shows microbial activity. The system, as we envisioned it, should foreground the soil itself, both during the assembly process and the deployment.

Initial explorations. To better understand the workings of Winogradsky columns, our team, consisting of designers, an environmental scientist and engineers, first cultured a variety of columns from soil we collected around Pittsburgh. In order to monitor these initial samples, we first augmented several plastic tubes with conductivity probes (description to follow). Columns were assembled and left on windowsills throughout our studio (to ensure natural light). Over the course of a month, we observed the transformations and measured changes in conductivity and voltage. When reviewing our notes, we discussed the different 'behaviors' across the columns: for instance, soil from a recently remediated dumping site for steel mills showed little activity (both visually and

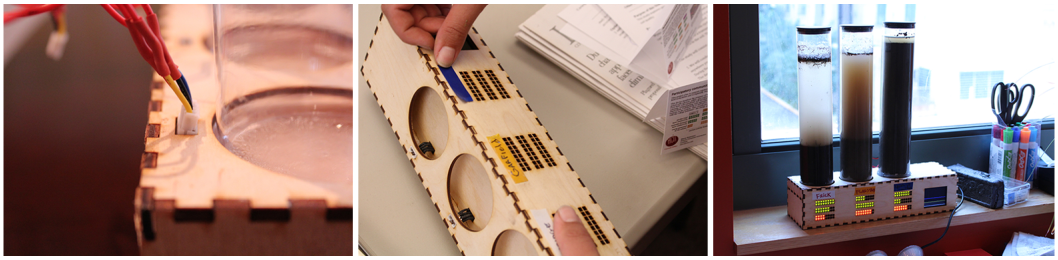

Figure 6.6. Designing a bio-electronic system: column plugged into casing; labeling the column slots; testing the system.

through digital measurements), while soil from a park developed a range of color gradients and large fluctuations in conductivity.

Materials and form. Observing these transformations led us to reflect on the form of the Winogradsky column and the possible forms that our final sensing system might take on. On one hand, the transparent column, which may be 10-15 inches tall and augmented with wires, is reminiscent of potentially off-putting laboratory equipment. At the same time, the soil and the common household items (eggshells, *etc.*) used for assembly are pervasive and familiar. Drawing on other form studies in HCI (*e.g.,* Gaver, 2010) we explored a range of material forms through sketches, 3-D printed artifacts, and low fidelity wood prototypes in hopes of complimenting the strange yet familiar aesthetic of the soil column. We also considered trade-offs such as *size*—a device that does not 'take over' window space, but still enables comparison between several samples, and *transparency*—a system that 'demystifies' the science behind soil microbiology and its digital measurements, without technology having an overwhelming presence.

Our final design consists of a wooden base with slots to fit three columns (2 inch diameter, total cost under $80). The columns can be 'plugged' into or detached from the wooden casing (Fig. 6.6) to support easier work with the soil itself. While wood—a soft and rather familiar material—conceals the internal wiring of the system, we left the wires leading to the columns intentionally exposed as a way of showing where and how the digital interfaces with the organic.

Electronics and behavior. Each column (plastic tube, 10in tall, 2in diameter) was outfitted with two conductivity probes, which were designed in-house: a 3D-printed enclosure houses two wires at a fixed distance apart. Conductivity is measured by an Arduino microcontroller, which pulses one of the wires at 5 Volts and reads the voltage drop across the second wire as current travels through the intermittent soil. LED matrices, embedded in the wooden enclosure below each column, show current column activity levels as three bar graphs: the top and middle green graphs represent conductivity in the top and bottom layers of the column respectively, and the bottom orange graph shows the relative energy generated by the column (Fig. 6.7). The readings are scaled based on maximum and minimum average values from the data we collected earlier, such that each conductivity bar represents a voltage drop of about 0.19 volts, and each orange bar shows a voltage increase of 0.045 volts. The data is sampled every thirty minutes and stored on an SD card inside the device. Conductivity levels of all three columns' bottom layers are plotted over time on a small LCD screen to the right. The system is powered by a 5 Volt power adapter, which plugs directly into the socket.

Testing. To ensure the system was working properly for prolonged periods of time, our prototype was tested over the course of four weeks. We assembled several new columns, along with various 'control' solutions of soil and water and 'deployed' the system locally in our studio. (Fig. 6.2). Though microbial activity is, in our case, largely unpredictable, we crosschecked the data recorded by the device with manual voltmeter readings. In addition, we checked that each tube that was augmented with probes remained waterproof. Working with microorganisms thus presented a range of design opportunities and constraints, and our design process, from initial explorations to the final testing, offered first-hand insights into how the system might be lived with over time.

6.2.2 Community deployments

Our system was deployed with two urban communities: a gardening center and an environmental outreach and conservation community.

Participating communities

We consider the groups we worked with to be early adopters of soil sensing technologies as they are already deeply invested in environmental issues. Founded in 1997 at the site of an abandoned gas station, the gardening community has been working to support and expand local gardening initiatives. The owners and

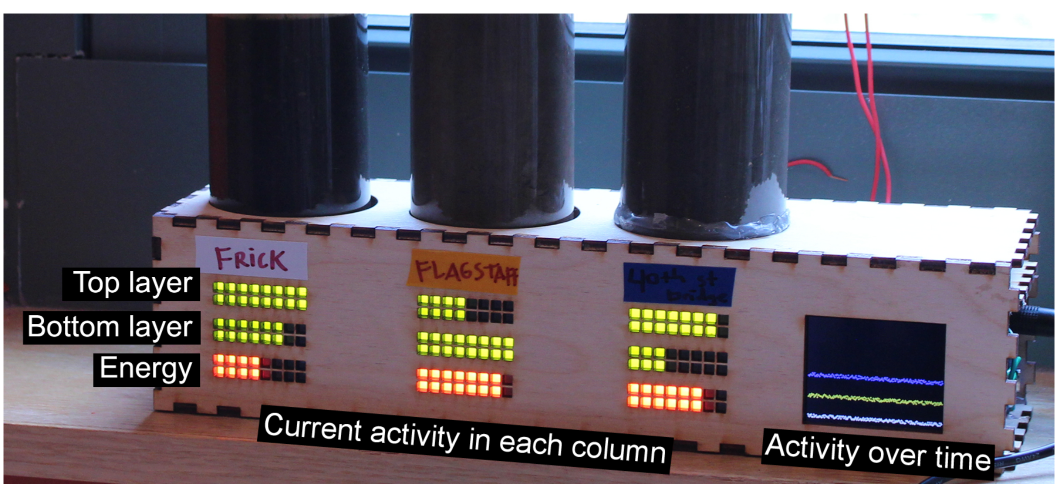

Figure 6.7. System visualization with components labeled.

employees offer a variety of services, from workshops and seminars to site visits that address plant health, landscaping design and pest control. The center also sells plants such as ornamental flowers, shrubs, and organic seedlings. The environmental outreach community—the second group we worked with—promotes education, economic empowerment and self-sufficiency amongst low-income residents. The group is hosted in a "green building", which opened in March 2012. The site serves as a meeting place for workshops, classes and programming for sustainability initiatives (increasing energy efficiency, lowering utility bills, *etc.*).

Workshops

Working with a community co-founder or coordinators, we organized soil workshops with each group. Workshops were advertised on mailing lists and forums, inviting participants to bring soil samples from any location of their choice. After a brief introduction, the workshops proceeded with an informal discussion of our city's environmental history. The workings of the Winogradsky column and our sensing system were then explained and participants were invited to assemble columns using their soil samples. The assembly process consisted of three steps, which were demonstrated by the organizers: 1) soil samples were diluted with distilled water; 2) shredded newspaper, crushed eggshells and gypsum were combined with the muddy soil at the base of each column; 3) the remainder of the columns was filled with a mixture of soil and water. After assembling the columns, participants tested their soil with several off-the-shelf kits. These tablet and strip style tests for potassium, nitrogen, pH, and lead indicated soil composition by comparing results with color-charts for 'high' 'low' and 'medium' values.

The materials (eggshells, newspaper, *etc.*) and test kits were provided by the organizers, along with the containers and tools for mixing the components. The workshops lasted 1.5 to 2 hours and were attended by 6 people (1 male) at the gardening center and 3 people (1 male) at the environmental center. Participants were of a wide age range (24-67) and backgrounds (*e.g.* gardening, art, physics).

Deployment

Workshop attendees decided to place the sensing system with the soil columns in prominent, high-traffic locations: on a windowsill in the meeting room at the environmental center, and in front of the check-out desk at the gardening center. The system was left at each space over the course of a month. Most participants (7 people) regularly interacted with the system several times a week while they worked or volunteered at the community space; one person checked on the device several times a month; and one person was unable to re-visit the space. To follow up on the project, we conducted phone and in-person interviews with workshop attendees and site visits to each space. We continue by detailing our findings, which are based on our field notes and audio recordings from workshops and interviews.

6.2.3 Findings

I present our findings in regards to five themes: hands-on making and storytelling during workshops, hybrid sensing materials, time, system interpretations, and discussions.

Hands-on making and storytelling

The workshops were held around large 'studio-style' tables, whereby participants cut newspaper, crushed eggshells, mixed soil with water (and literally got their hands dirty) to assemble Winogradsky columns (Fig. 6.8). Our attendees described the making process as interesting, engaging, and fun, and were visibly immersed in it. Unlike many DIY environmental sensors, however, the Winogradsky columns can be assembled without any technical knowledge (no electronics or soldering). Our participants, who had backgrounds ranging from biology to art, psychology and gardening, all described the process as easy.

Also unlike participatory sensing workshops that use electronics or prototyping tools brought in by the researchers, our workshops involved materials from the attendees—soil samples they dug up from their backyards and gardens. Participants selected soil from locations that they suspected to be polluted or nutrient deficient. For instance, one person brought soil from a community garden, explaining that she was concerned about a potentially toxic termite spraying and rubber mulch nearby, while others selected places where plants did not seem to grow well.

As they assembled the columns, participants shared speculations about past experiences with their soil. In an excerpt below, a participant described conditions in his backyard, attributing poor growth to either soil or shade:

> "It's got clay, it's got charcoal, some shale I think, I don't know what else… stuff will grow, but it is in the backyard, it's under trees so it doesn't get a lot of light. I just started planting like shady stuff in there. I had a fern and some hostas that lived, but then by Columbus Day, they just withered up and died." [P4]

While the above speculates on natural factors (soil composition and shade), often the narratives also referenced Pittsburgh's environmental past:

> "Mine [soil] is from my back yard, which, when I moved there 40 years ago, I looked at the backyard and it was this rich black black black soil and everything I put in would just go [sigh, withering hand motion]. It was that much soot, basically from Pittsburgh and from fire furnaces and just the pollution, collecting for years." [P8]

Here, a participant recalled seeing her soil for the first time, linking poor plant growth with pollution from mining.

Figure 6.8. Community soil workshops: using a potassium test kit, mixing column contents, sensing system placed by cash register.

To summarize, our system required DIY assembly of its organic components. Our workshops thus necessitated participants' hands-on involvement with soil, both while collecting samples and making the column, and these interactions prompted narratives around local soil quality.

Hybrid sensing materials

The integration of digital and organic materials into a single system was not unusual for our workshop participants. As it turns out, the majority of attendees already work with a combination of digital sensors and living indicators in their daily practice. Many of the participants (7 people) had previously tested their soil using digital means. Most commonly, samples were sent to a lab, which returned a breakdown of nutrient levels such as phosphorus, calcium, pH, *etc*. Participants also relied on observation and interactions with living systems to understand the environment: from day-to-day inferences about soil conditions based on plant appearance, to organizing workshops that educate the public about beneficial and pest insects, to more scientific dissections of fish to track hormone pollution in a local river, our participants were 'experts' in a range of hybrid systems.

It is therefore not surprising that they fluidly switched between observing the digital display and the soil itself in our system. The excerpt below reflects how both the digital bar graphs and the organic processes were drawn upon:

> "With the lights, it would be like hey, your stuff is doing a bunch and my stuff isn't, but actually seeing that soil though too it was… I mean I kinda liked that because I guess you know what's going on, you see the differences, the bubbling at the top in the water. Sometimes some of them would create some bubbles, stuff like that, the separation of it." [P4]

Likewise, other participants described taking a glimpse at the 'lights' (bar graph displays) to quickly determine how active their column was in relation to others, while the soil columns themselves were observed more carefully:

> "You can actually see what's going on in your soil, cause that's what it is, um just like a little slice of life there." [P5]

> "I guess just the visual aspects of it, being able to track it just being able watch it progress." [P7]

> "In the column you can see what's going on because it's in a glass container that you can watch any day, whereas in the yard you really can't take a look at it." [P3]

As these excerpts suggest, participants appreciated being able to *see* the processes in the soil in addition to the digital measurements. This combination was, in a way, perceived as more transparent than lab-based soil testing:

> "It was nice to have a visual thing, instead of… I guess as opposed to sending a soil sample away where you have no idea what's happening." [P4]

> "I also like the fact that you could do it yourself where if you're sending something off to a lab you don't know how it's being handled or who's doing it and is it going to be accurate, where this is in your own hands and you can kind of judge on your own," [P5]

In the above excerpts, participants describe how assembling and observing the soil columns first-hand gave them more control than 'black-box' testing. In other words, what made conventional testing methods seem doubtful was the perceived distance between the participant and his or her soil, as well as physical separation of the soil from the digital (or paper) test result. Our design, on the other hand, enabled participants to draw upon both the digital and organic aspects of the system, and this juxtaposition was seen as more transparent than other modes of soil testing.

Time

While many digital sensors respond to environmental conditions almost instantaneously, changes in the soil columns and display were only apparent after several days, and the system continued changing over the entire month.

> "I definitely remember after the first couple of days, there were some lights on, and it's definitely grown in the past 3 weeks." [P1]

P1's use of the word "grown" above is not incidental: all participants talked about the system as growing, evolving, or progressing over time. In the context of other natural processes, participants did not see our system's timescale as being particularly surprising or even slow. In the passage below, P4 contrasts how technologies, such as internet connection speeds, have advanced to be much faster than the timescales of living things (*e.g.,* gardening):

> "There are things that in real life they just take longer to do. Some things don't happen that fast and on the whole we're spoiled now and I find myself the same. It's like surfing the web, when it used to be dialup... now when I sit there and I have to wait you know ten seconds for a page well I'm like, what's going on, why isn't doing anything? And it used to be you'd walk away and get a cup of coffee. That [the soil system's time] seems fine to me and especially in the timeframe of like gardening and that kinda thing, that stuff takes time anyway." [P4]

It's important to highlight P4's distinction between digital speeds (and our expectations of them) and the speed of things in *real life*. Likewise, P7 differentiates between faster results from test kits used during our workshops as opposed to the long-term observation of the soil columns:

> "I prefer the slow methodical side of technology to the instant gratification, sort of things… It's just interesting to see how things need to settle and to react and that doesn't happen instantaneously so I guess I can appreciate that… The results of the other tests are sort of about the instant gratification and

> instant readings. I think it's really cool to be able to track things and follow things… it's more fun and engaging."[P7]

Thus, while our participants perceived the timescale of our system to be appropriate and even engaging, they saw it as operating outside of 'faster' digital technology paradigms. That is, the slowness seemed appropriate because our system was more similar to an organic process (*e.g.*, growing a plant), than to digital tools such as the Internet.

System interpretations

On an individual level, the system inspired reflections on the overall "health" of the soil and how it related to broader ecological processes. The passage below, which was prompted by a discussion about the energy generated in the soil columns, relates soil activity to the human food supply:

> "It [soil] grows everything we need, it has to be alive to give back to the plants, and I figure… plants need a certain amount of bacteria and certain amount of nutrients. We need a certain amount of nutrients and so we eat food to get the vitamins and nutrients that we need in our body and a soil does the same thing, it needs nutrients to grow [plants] anything and keep everything going. It tries to rejuvenate itself with microorganisms and the other bacteria, I mean not harmful bacteria but bacteria that's good for growing and helping the dirt." [P3]

It's important to note that P3 draws a connection between non-harmful bacteria in the soil and the production and uptake of nutrients in the human body. Another example relating the soil to larger systems is P5's observation that bacterial activity was linked to weather patterns:

> "It's interesting, it seems like when it's sunnier out they're [organisms in soil] all a little more active in there… I mean it's more lights, the lights are over farther and umm there tends to be more. If I do have any aerobic activity it's when it's a sunnier, hotter day, and one thing I really noticed is as it got later in the day the light umm were shorter." [P5]

What's interesting here is P5's use of the digital display (the variation in the "lights") to establish a connection between bacterial activity and sunlight. These broader reflections contrast how participants talked about results from more standard lab-based or kit-based soil tests:

> "There's usually a recommendation on it [soil test] to add, you know lets say 2lbs of umm 10-10-10 fertilizer per 100 square feet and so we help them [customers] pick out that fertilizer that works for them." [P9]

> "Phosphorus is supposed to be good to grow things but my soil was kinda depleted with it so I think what I could do is use a fertilizer with phosphorus in it and try to get it back into the soil." [P3]

As suggested above, tests that reported levels of compounds in the soil cued participants to a very specific course of action: *e.g.*, if a nutrient deficiency was detected, participants added the appropriate compound to the soil (or instructed the clients to do so). Thus, while such test results were directly actionable, they served to narrow participants' focus. The following quote best summarizes this point:

> "A test is just like you know nitrogen, potassium, it kind of doesn't tell you really the overall health and what's going on in there, the activity." [P5]

As noted by P5 and others, though our system did not explicitly report specific levels of compounds such as nitrogen or potassium, it provided a more holistic representation of soil and the biodiversity of life within it.

Sharing and discussion

The physical juxtaposition of participants' soil samples, which were from all over the city, inevitably inspired comparisons. For instance, in the following excerpt, P9 describes how the system was discussed within the group:

> "We thought it was interesting since his soil and [another person's] soil came from the same area they were having better results and more reactivity and mine being so far away from the city was getting such different results." [P9]

Since the system was placed in prominent locations at both community spaces, it also facilitated conversations with visitors, customers and collaborators. Coordinators at both spaces noted that people would ask about the project (*e.g.*, "oh, what is that?"), and this would usually prompt a discussion. In addition, several participants mentioned the project to friends and family members that had backgrounds in biology, environmental science, or similar:

> "I also I mentioned it to a friend who works for the [local] conservation district and was an environmental science major, we sort of discussed it briefly I told him like oh I was involved in this little experiment and explained to him, you know Winogradsky columns and how it worked and he was really interested in it." [P9]

In the above, P9 recalls discussing the project with an environmental scientist who works for a conservation district. When envisioning how the system might be used in the future, participants suggested deploying it with other gardening communities, food co-ops, and environmental education programs.

6.2.4 Discussion

This section detailed the design and deployment of a bio-electronic hybrid sensing system. In particular, I have highlighted how incorporating organic materials into the design revealed new challenges and opportunities for the research team. For instance, the longer timescale of the microbial development necessitated that the researchers observe the system for prolonged periods of time, much like the participating communities did during the later stages of the project. The integration of digital with the organic also raised pragmatic concerns, as not many tools exist to support easy prototyping with these new materials. From low-cost devices that maintain certain environmental conditions (light or temperature settings), to tools that interface organisms with current platforms (*e.g.*, Arduino or mobile phones), to broader sharing mechanisms that provide starting points and "hello-world" examples, HCI research has much to explore. Likewise, infrastructure-level issues—transportation, storage, disposal, *etc.*, remain unexplored.

The juxtaposition of organic and digital elements also shaped the form and appearance of the system. In the final iteration of the project, most of the electronics were housed in wood, while also transparently interfacing with the soil through the Winogradsky tubes. Participants' experiences with the system reflected some of these design decisions: community members fluidly drew on organic and digital representations of soil development, and used the system to more broadly reflect on technological timescales, as well as processes in surrounding ecosystems.

Ethical considerations

While bio-electronic systems such as ours present many trajectories for HCI research, it is important to critically reflect on possible ethical issues and unintended consequences that could emerge from working with organic materials. Although our work incorporated naturally-occurring bacteria, and arguably did not raise contentious issues, HCI work with living organisms such as insects or animals raises new questions. These range from safety issues of handling organisms that may affect human health, to ecological considerations, such as, for instance the accidental release of invasive species. More broadly, there are clear philosophical and moral issues surrounding the reduction of living systems to digital inputs and outputs, and the fair and humane treatment of living organisms. These issues must be considered as the HCI community moves forward with designing hybrid systems.

6.3 Summary and implications

In the literature review (Chapter 2), I discussed how publics integrate heterogenous materials and values into the making of *things*. In particular, I highlighted Latour's framing of technoscientific objects, which aim to convey matters of fact, and things, which instantiate matters of concern by giving material form to issues, narratives, dialogues, and sensor data (2005). Building on these ideas, the systems presented in this chapter trend towards the latter—they aim to reveal environmental processes, scientific information, and local concerns in new ways through the coalescing of different materials and stakeholders. New knowledge was gained both through the design of these systems, as well as through their deployment in the real world. In this way, our research approach has been aligned with Fallman's view of *design-oriented research*: new knowledge is uncovered through the construction of the artifact and the study of its use (Fallman, 2008). In what follows, I more broadly reflect on our findings from working with the paper-based and the bio-electronic systems and suggest opportunity areas for future citizen science research.

6.5.1 Seamfully interweaving hybrid materials

As I discussed in Chapter 2, seamful computing celebrates points where diverse materials, as well as people, technologies, and contexts coalesce (Chalmers, 2004). These intersections serve as generative areas where new knowledge and practices can emerge. Our sensing systems operate at these junctures: the air monitoring system incorporates paper materials and the physical particles in the air as part of the visualization of pollution; while the bio-electronic system interfaces soil, which is itself a complex hybrid of bacteria, nutrients, metals, *etc.*, with electronic conductivity probes and digital displays. This "seamful interweaving" reveals a range of new constraints and insights. For instance, the Winogradsky columns' slower timescale, light and temperature requirements, and unique physical form necessitated an immersive design process within our multi-disciplinary team. The resulting physical interaction with the soil—an organic and arguably more familiar material than digital sensors—led to community knowledge sharing through narratives during the deployment. Likewise, familiarity with paper materials enabled participants to quickly assemble their own sensors and view the results, without being put off by the 'lab-like' qualities the microscopes. The physical involvement in the construction of the system itself supported a sense of '*affirmation*' in the data.

These insights are aligned with my findings in Chapter 5, which suggested expanding HCI's vision of sensing to include organic and analog materials. Future sensing systems can leverage other soft materials and living organisms, from bacteria to plants, insects and entire ecosystems as inputs and outputs into digital technologies. To be specific, future research might include: a water sensing system that cultures bioluminescent bacteria in different water samples to show levels of toxicity by digitally tracking colony counts; a monitor that analyzes a plant's response to air exposure across urban areas; or a bioremediation system where sunflowers, which leach metals out of soil, are coupled with digital lead sensors.

Biological and physical systems are, by definition, active and embedded in our surroundings. Recall, for instance, that our participants discussed the soil columns as 'evolving', 'growing', and being a 'slice of life'. In other words, participants treated the materials being sensed (bacteria, air particles, water, soil, *etc.*) as active agents in the sensing system. We see this as parallel to how material properties both guide and constrain the practice of craft in Rosner's account of "materials *having a say* in the [book] binding process" (2010). This view shifts our understanding of systems from being purely machine, to considering how living organisms (bacteria, birds, humans, *etc.*) interact with complex materials (paper, air, water, soil, digital artifacts, *etc.*).

When incorporating non-digital materials and organic processes into the design of systems, we inevitably confront questions of form. For instance, the strange yet familiar qualities of the Winogradsky column were highlighted by the aesthetic of the final system. Similarly, the particulate pollution sensors showed where the sample was being collected, transparently linking the physical collection of particles with their digital representation through a microscope. With form being essential in design research, such as, for instance, in the design of Gaver, *et. al*'s *Prayer Companion* (Gaver, 2010), it is critical to consider what new forms might emerge as analog, organic, and digital materials are combined into transmaterials, hybrids and composites. This suggest opportunities for work incorporating 'active' materials—pollutants, bacteria, plants, animals—into sensing systems. For instance, soil composition could be visualized and evaluated through soil chromatography—a technique whereby soil compounds are separated and visualized on paper by capillary action[29]. Likewise, communities might track water quality by viewing water samples from local streams and creeks through a microscope, magnified glass, or microscope-enabled mobile phones[30]. These hybrid, materially-oriented approaches might radically shift our understanding of what a 'sensor' looks and feels like, as well as what it means to 'read' it.

6.5.2 New ways of seeing

Both sensing systems enabled participants to see environmental processes, scientific instruments, and surrounding contexts in new and different ways. Most directly, the air sensing approach revealed the physical particulates in the air, enabling participants to observe the specific pollutants they were interested in—diesel truck, construction, or coal plant emissions—as well as to reflect on causes of particulate pollution they have not previously considered (*e.g.*, traffic exhaust). Moreover, participants envisioned using this system to track complex processes, such as the movement of polluted air across the topography of the region, which may not be captured by single-point professional sensing such as the AQI. Likewise, the organic and digital components of the soil system were fluidly drawn upon over time to infer the 'overall health' of the soil, or link the system with broader processes such local weather.

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29 Similar to this soil chromatography method. http://milkwood.net/ 2011/11/06/soil-chromatography-with-eugenio-gras/

30 See http://hackaday.com/2011/10/19/cellphone-microscope-for-about-20/ or http://hacknmod.com/hack/turn-an-iphone-into-a-microscope-for-10/; as well as CellScope http://cellscope.berkeley.edu/

These deeper engagements with context contrast participants' interpretations of soil tests for specific factors (pH, nitrogen, *etc.*). These quantifiable measurements offered what one participant called 'instant gratification': upon seeing the results, participants made specific judgments and took action (*e.g.*, adding fertilizer). This type of sensing is not unlike digital devices that report on one or several factors such as particulate pollution in the air. In a way, such sensors operate as perceptual 'filters', revealing details that are otherwise imperceptible, albeit, at the expense of narrowing our focus. This approach can be extremely valuable, especially in cases directly involving human health (*e.g.*, detecting toxin levels in a water supply). However, recent literature also notes ways that this 'narrowing' can potentially disengage users from the phenomena being sensed: an auto-watering system might discourage presence in a garden (Hirsch, 2010); GPS navigation might disengage drivers from their surroundings (Leshed, 2008).

Embracing pluralist qualities

Complimentary to sensing devices that report on specific factors (parts of a whole), new research can focus on revealing processes within and across *systems*. Rather than facilitating specific judgments about the world (*e.g.*, I need to add fertilizer, *etc.*), systemic approaches can expand our focus by leveraging more holistic and less precise inputs and outputs. For instance, a community garden system might show bee flight patterns, beneficial and pest insect presence, or plant leaf discoloration, while a river system might reveal fish behavior, plankton populations, or bird activity, possibly in conjunction with digital data such as soil pH or particulates in air. These approaches may result in systems that are more physically connected to the phenomena being sensed. Moreover, by highlighting these broader relationships, systems will likely embody pluralist qualities of interaction and support multiple intuitions and interpretations (Bardzell, 2012). These approaches will shift from prescription to reflection and serve to focus our intuitions, deliberations, and discussions '*around a topic*' (Sengers, 2006; Brynjarsdottir, 2012).

Slow and prolonged engagement with systems

With these more holistic approaches, design can move towards supporting prolonged engagements with systems. Given, for instance, that our participants found tracking the columns over time to be 'fun' and 'engaging', future work might leverage more 'natural' timescales. The slowness of some biological systems, as well as the longer time it took to collect air quality particles, presents a compelling contrast to many digital sensing implementations, where devices immediately respond to pollution levels and present data in 'easy-to-read' literal formats (*i.e.*, numeric scales). Future work might include: a digital sensor that enables groups to track the growth of a bio-indicator plant over several months; a mobile platform that helps participants learn about pest and beneficial insect populations; or a living system such as a beehive, that is cared for by communities over several years.

6.5.3 Hybrid systems as vehicle for collective action

New ways of seeing can bring about new modes of participation. On one hand, stakeholders might take on more active roles, similar to how our participants assembled parts of the sensing systems—the particle sensors and the soil columns, and collected local air and soil samples. More broadly, as deployment shifts from a 'one-off' usability study to studying how a system is *lived with*, stakeholders can be more involved in constructing and nurturing its parts. This suggests opportunities from individual kits that require DIY assembly, to platforms that enable communities to build their own sensing systems, to digital or organic systems that are more reliant on our attention and care.

In addition, as we move towards more complex systems, participation shifts beyond the individual. First, sustaining and understanding living systems requires more nuanced skills than is usually required for interacting with HCI's participatory sensing devices (*e.g.*, a heatmap of high/low air pollution levels). As we found in our research, such knowledge is often tacitly shared within and across communities through workshops and seminars. HCI can support these practices by developing scaffolding tools, including rich new ways for annotating organic processes with metadata by experts to be shared with novice users, as well as communication platforms that nurture mentor-apprentice relationships within communities. Second, participation can extend across communities to further the co-production of knowledge between scientists and hobbyists. During our deployments, for instance, participants reached out to people with scientific backgrounds to share the projects, and envisioned our systems being used a environmental education tools. For HCI, this implies new opportunities for enabling 'open source science' (as I discuss in the next chapter) from more direct data sharing and discussion tools that bridge the work of scientists and non-experts, to crowdsourcing, and extensions into online communities. These more nuanced modes of participation, which move beyond individual behavior change and towards richer collective experiences of nurturing natural sensors.

6.6 Conclusion

This chapter detailed the design of two hybrid systems: 1) a paper-based particulate pollution monitoring approach; and 2) a bio-electronic sensing system that visualizes microbial activity in soil. These systems operate across a range of materials—from organic to analog and digital, and their deployment with urban communities revealed a host of observations, narratives, and concerns. Above all, our findings suggest moving beyond discreet, digital representations of environmental phenomena and towards more holistic systems that materialize local processes and issues. In short, I have argued for seamfully interweaving organic, analog, and digital materials to create new assemblies and new ways of seeing.

7 At the seams: designing for open source science

So far my dissertation has addressed processes that bring citizen science publics into being: expressing concerns through sensing and tangible media, gathering knowledge amongst expert practitioners who rely on biomarkers, and making hybrid systems that materialize scientific data and local concerns. The next two chapters turn to new forms of science practice that have been largely overlooked by traditional HCI research: groups of people who participate in biology and genetics. My work, which includes extensive field interviews, workshops, and physical prototyping, explores how these new modes of science making are giving agency to emerging 'biocitizen' communities.

This chapter focuses on DIYbio (Do It Yourself Biology), a growing community of hobbyists, artists, hackers, and scientists experimenting with biology outside of professional laboratories. From independent bioartists, to meet-ups of hobbyists and professionals, biotech non-profits, and fully-functional grassroots laboratories, the 'garage biology' movement is reconfiguring, tinkering, and playing with organic materials and systems (Fig. 7.1). I begin with an summary the DIYbio community's origins along with an overview of what we found be its key characteristics and motivations[31]. I then report on our in-depth work with several open source DIYbio tools, including OpenPCR, a low-cost thermal cycler and the Pearl Blue transillumintor for visualizing electrophoresis results. These tools were first studied in a professional laboratory, and then deployed in workshop, whereby members of a local hackspace tested food products for genetic modifications.

Figure 7.1. Swab sample collected by DIYbio Manchester, image source http://diybio.madlab.org.uk/; sterilization with pressure cooker at Bosslab, image source http://bosslab.org/; algae biofuel project at London Hackspace.

[31] Parts of this chapter were previously published (Kuznetsov et al., 2012)

Drawing again on the seamful computing framework of Chalmers, et. al (2004), I discuss three seams that emerged from our research: i) DIYbio and professional biology; ii) DIYbio and the general public; and iii) hybrid materials of living organisms and digital technologies. To envision HCI's role across these intersections, I present three design exercises (functional prototypes) that help provoke and shape future research trajectories. Each exercise serves to suggest implications for interactive systems at the seams of biology, computation and public engagement.

7.1 DIYbio practices and materials

7.1.1 Methods

My research of DIYbio practices, materials, and origins involved several strands of investigation. The work began by surveying the history of the DIYbio movement—as detailed in Wohlsen (2010), Carlson (2010), Ledford (2010) and others—and by reviewing numerous DIYbio community blogs and mailing lists[32]. As another entry point, we organized a workshop with professional and DIY biologists near London, UK. The workshop included presentations, discussions, and structured brainstorming. Themes derived from these were used to conduct follow-up site visits to three professional biology labs in the UK and two DIYbio communities in London and Manchester, each lasting 2-3 hours. In addition, we conducted phone interviews (1-2 hours each) with founders of five major DIYbio groups internationally. In total, we surveyed seven DIYbio initiatives in four countries:

- Genspace, New York, USA. genspace.org
- BiologiGarden, Denmark. biologigaragen.org
- Bosslab, Boston, USA. bosslab.org
- Manchester DIYbio, UK. diybio.madlab.org.uk
- Indie Biotech, Dublin, Ireland, Indie Biotech.com
- London Hackspace, UK. london.hackspace.org.uk
- Biocurious, Sunnyvale, CA biocurious.org

[32] Examples include Biopunk http://biopunk.org/; DIYBio, http://diybio.org/; The Open BioHacking Project, http://biohack.sourceforge.net/ and others

We also interviewed a bioartist in the UK, and a biologist at the UN Office for Disarmament Affairs in Geneva, who works on ensuring safe (non-hostile) use of biology. Interview audio was transcribed and coded to themes.

Limitations

The findings are based on discussions with participants, and are thus susceptible to self-selection bias. In particular, the people who agreed to speak with us tend to collaborate with academic researchers, and our findings might not be generalizable to other types of practitioners, for instance 'outlaw biologists' (Kelty, 2010) working independently. I also note that our phone interviews do not provide insights into the details of routine DIYbio work. Rather, I present participants' reflections on this emerging space, and follow up research might focus on understanding in-situ work practices. I continue by detailing findings across three areas: i) origins and motivations; ii) materials; and iii) public engagement.

7.1.1 DIYbio origins and motivations

Scientific inquiry is often furthered by chance inventions ('hacks') and breakthroughs, such as, for instance, the accidental discovery of penicillin or the adoption of a jam ingredient, agar, as a growth medium. As noted throughout DIYbio literature and mentioned by many of the participants, these examples along with a host of artistic and socio-political influences serve as an inspiration for DIYbio. However, of particular importance has been the development of a novel research area: synthetic biology.

Synthetic biology and iGem

An emerging field itself, synthetic biology explores "the design and construction of new biological parts, devices, and systems" and "the re-design of existing, natural biological systems for useful purposes"[33]. Alongside this articulation of biology, the field also introduced initiatives that unsettle the status quo in biological and, more broadly, scientific modes of inquiry. For instance, it has been remarkably open to collaborations with designers and social scientists, as well as engineers. This openness is also reflected in its public sharing of information through forums such as OpenWetWare[34]. Countering the trend of keeping research proprietary, OpenWetWare readily states its aim "to promote the sharing of information, know-how, and wisdom among researchers and groups".

[33] Synthetic Biology. http://syntheticbiology.org/ Accessed February 2013.
[34] OpenWetWare. http://openwetware.org Accessed February 2013.

Similarly, the annual International Genetically Engineered Machine competition (iGEM)[35] presents a radical shift for the modes of knowledge dissemination in traditional science research. Instead of adhering to longer processes and formal requirements demanded by scientific publications, iGem teams work in short timeframes and creatively experiment with a Registry of Standard Biological Parts[36] to design new biological systems and, as they refer to them, 'devices'.

Framed in these terms, synthetic biology is presented as a field that just might be dynamic and innovative enough to harness the engineering potential of biology and in doing so, address some our most pressing challenges (Carlson, 2010). Undoubtedly, this rhetoric has been an important trigger for the DIYbio movement. A famous early DIYbio example is Katherine Aull's homemade test for hemochromatosis—a genetic blood disorder resulting in over-absorption of iron in the body. Aull was able to accurately test herself for this disease[37] in a lab she built in her home closet using equipment from e-bay. DIYbio is thus inspired by research and discovery, but as we present below, less emphasis is given to strictly reproducing results and more to enabling open access to the scientific experimentation and the tinkering itself.

From synthetic biology to hacking and biohacking

By associating itself with an openness and, in particular, with open-source (*e.g.*, Drew, 2005), synthetic biology at once identified biology as a resource for tinkering—or 'bio-hacking'—and a platform open to everyone. Hence it is not surprising that DIYbio cultivated a close association with hacker cultures and practices. For instance, CodeCon, traditionally a computer hacking conference, featured Meredith L. Patterson's talk on DNA purification techniques using household items in 2005[38], and dedicated one third of its program to a biohacking track in 2009. Many of today's DIYbio groups including Bosslab, DIYbio Manchester and BiologiGarden are hosted within existing hackspaces, while others (*e.g.*, Biocurious, Genspace) regularly collaborate with local DIY groups.

Similarly, DIYbio's motivations appeared to emerge from the conjoining of synthetic biology and hacker/open-source movements. As the co-founder of Genspace explains, the ability to access science outside of traditional institutions is in itself a primary motivation for DIYbio: "*So our main goal is to make synthetic biology happen… I want to view it more as making science itself more accessible*." In addition, what appeared to catch the imagination of DIYbio founders and the fledgling

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[35] International Genetically Engineered Machine competition. "Synthetic biology based on standard parts". http://ung.igem.org/

[36] Registry of Standard Biological Parts. http://partsregistry.org/Main_Page

[37] Johnson, C. Do-it-yourself genetic sleuthing. *Boston Globe*, May 11, 2009

[38] Patterson, M. L. How to Purify DNA Using Common Household Items. http://maradydd.livejournal.com/. Accessed February, 2013.

community, were flexible ideas of experimentation and creativity. In the words of Bosslab and DIYbio.org co-founder, "*You should be able to build things that are cool. And that's the reason to do stuff in and of itself.*"

To varying degrees, all of our interviewees emphasize the value of creative tinkering and the fun of "playing with science", but this hands-on experimentation is closely coupled with wanting to learn. For our participants, DIYbio serves as a resource for understanding information that has been traditionally limited to academic literature or unavailable altogether due to expensive access to publications outside of academic settings, for instance. Thus, equally important, though less emphasized, is DIYbio's aspiration to disrupt conventional patterns of knowledge dissemination in academic research.

The motivations outlined above—open access, creative tinkering, learning, and unsettling traditional modes of science making—echo values embedded in many previously studied DIY and hacker communities (*e.g.*, Torrey et al., 2007). Unlike other DIY groups however, the resulting DIYbio community remains embedded in and dependent on the discourse between professionals and non-experts.

7.1.2 DIYbio communities

What evolved is a loosely coordinated community of distributed DIYbio labs, engaging with biology through hacking and tinkering outside of traditional institutions. The DIYbio.org organization[39], founded by Mackenzie Cowell and Jason Bobe in 2008, serves as a meeting point for practitioners around the world. The public mailing list boasts over 1900 members—from professional scientists and biotech entrepreneurs, to artists, founders of DIYbio labs, and hobbyists with no biology background.

> So DIYbio is one source of like hey, I want to do blank what do I do. There's a lot of people on there who are PhD students or who are scientists or have done this, a lot who will chime in and say oh yea do this… so you can just like interact with a spectrum of practitioners. [P2]

Above, DIYbio.org's co-founder, who himself holds a biology degree, emphasizes the role of expertise in sharing DIYbio knowledge. Indeed, to varying degrees, all DIYbio groups we surveyed serve as platforms for collaboration between professionals and non-experts. We now briefly summarize the workings of three initiatives—Genspace (USA), Indie Biotech (Ireland) and Manchester (UK)—as a diverse cross-section exemplifying these relationships.

Genspace

Genspace[40]—one of today's most active DIYbio labs—was started by two undergraduate students, a science journalist and an employee at a biotech

[39] DIYBio. http://diybio.org/
[40] Genspace, New York City's Community Biolab. http://genspace.org/

company as a meet-up in New York City in 2009. The group was hosted at NYCResistor, an established non-bio hackerspace. They grew to include eleven active members and eventually established a BSL1-certified lab within a collective of artists and engineers in Brooklyn. While Genspace models their community on the hacker space design patterns, their work is informed by feedback from professionals:

> From early on we found out that we couldn't really build and run… a biotech lab whether it's DIY bio or community or synthetic biology or whatever… We really needed to get in touch with people who are actually doing biological research could help us out, give us advice. [P5]

Consequently, Genspace is affiliated with an advisory board of scientists who assess safety procedures and back the group's biosafety certification. By aligning themselves with professionals, Genspace also receives equipment from laboratories that move, downsize or upgrade. Today, Genspace is self-funded and open 24-7, hosting a variety of projects that focus on topics such as biological lasers, temperature biosensors and microscopes from webcams, as well as running many public workshops and classes.

Indie Biotech

Indie Biotech[41] is a startup company in Ireland, aimed at creating affordable equipment and methods for practitioners working outside of academically funded labs. The founder, Cathal Garvey holds a genetics degree and works in a lab he built in his parents' house. Gravey emphasizes the importance of science "*in the hands of individuals, not corporations and governments*", and is thus the first individual to acquire an EPA certification for working with genetically engineered organisms in Ireland. His most recent project is a new plasmid for Bacillus subtilis—a laboratory-safe strain of bacteria—to make DIYbio projects safer, more reliable and antibiotic-free. Earlier, he also developed the dremelfuge, a 3D printed accessory that can be attached to a regular dremel and serve as a centrifuge. Like the rest of Indie Biotech's products, the dremelfuge costs a fraction of the price of its professional counterpart (Fig. 7.2).

Manchester DIYbio

This UK community formed in March 2011 as a collaboration between Manchester Metropolitan University and Madlab[42]—an independent hackspace. Professors partnered with Madlab as part of the university's Nano-Info-Bio program, which supports interdisciplinary research and public engagement with science. The resulting DIYbio initiative is funded by the WelcomeTrust, UK's largest independent charity for medical research. The group's monthly meetings

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[41] Indie Biotech. http://www.indiebiotech.com/, Accessed 2013

[42] DIY Biology: Manchester "citizen science" in actionhttp://diybio.madlab.org.uk/, Accessed 2013

tend to be led by the core organizers (mostly academics) but involve hands-on participation from all attendees (usually 20-30 people). For instance, during the first project, Swabfest, participants collected swab samples from local bus stops. These were cultured by the organizers at Madlab, and participants returned to conduct colony counts later. While initially intended as a 'bootstrapping' exercise to teach swabbing techniques, interest in the data inspired a Microbe Map visualization. More recently, the group is breeding snails to select for certain traits.

So far, I have outlined the origins and motivations of the DIYbio movement, as well as the workings of its several initiatives around the world. I have shown that DIYbio is closely aligned with pre-existing hacker cultures by embracing tinkering, creating play and open access to science outside of professional settings. Nevertheless, individuals with professional biology backgrounds form the core of this community, from sharing technical knowledge through DIYbio.org, to advising on safety procedures or engineering new materials such as modifications to the Bacillus subtilis plasmid. DIYbio thus creates a hybrid space for professionals and hobbyists with varying degrees of expertise, and emerges from the discourse at this intersection. Inspired by the interplay between synthetic biology and 'open source' values, this space supports "new ways of science-making", including bioart, biohacking and citizen science, which do not exist inside or outside of professional biology but within it (Kelty, 2010).

7.1.3 DIYbio materials

The materials used by DIYbio practitioners—both to conduct experiments and to experiment on—also tend to merge professional and DIY domains. For instance,

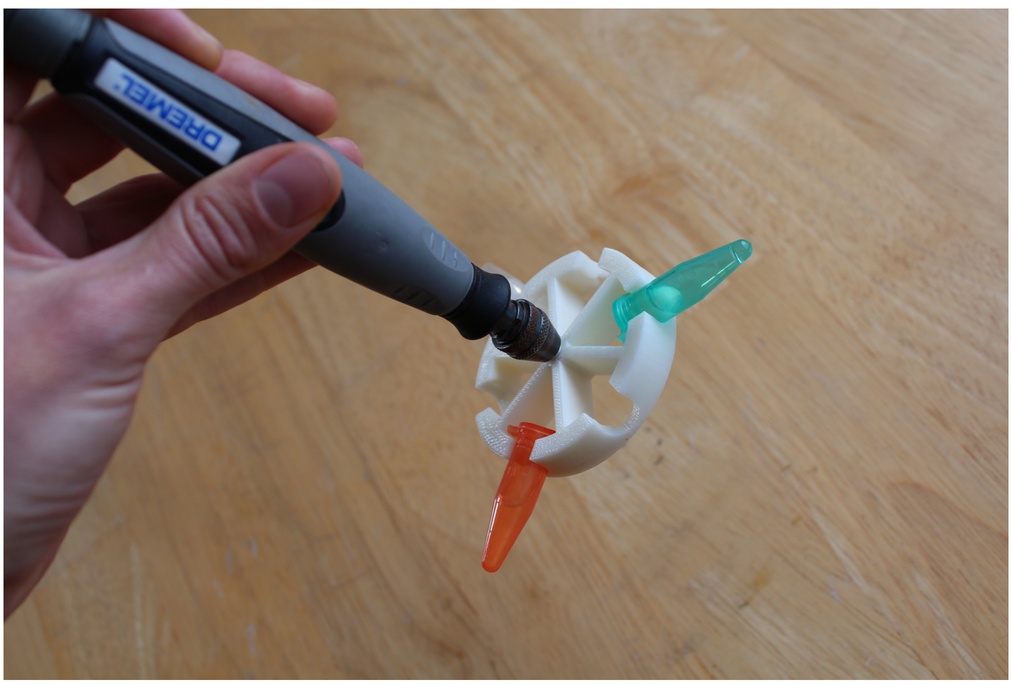

Figure 7.2. Dremelfuge developed by Indie Biotech.

DIYbio labs were found to exploit the broader developments in biology R&D. Biotech companies upgrade or relocate, and universities purchase new equipment, resulting in a large turnover: from microscopes and incubators, to glassware and chemicals, materials are being discarded or replaced. Each DIYbio group had its own ways to take advantage of this situation. Genspace inherited a range of tools and chemicals from a closing biotech company, much of Bosslab's equipment was donated by a university, Indie Biotech acquired glassware from a local charity, etc. It's notable that while many of our participants described donations as easy to find, others worked hard to establish relationships with local facilities. For instance, Dr. Ellen Jorgensen, one of Genspace's founders, has served as the primary liaison between Genspace, New York's universities and biotech companies.

In many cases, DIYbio groups also spoke of having to circumnavigate institutional policies. Certain materials such as primers, dyes and cell cultures are necessarily purchased from biotech distributors. However, larger suppliers cater almost exclusively to professional laboratories, forcing DIYbio groups to find ways to register as legitimate organizations with the suppliers or to order from smaller companies. As Bosslab's founder explains below, his lab's website serves as an important resource for gaining credibility in such cases:

> They'll [biotech distributors] call you and find out if you're a real business. Like my lab had a sketchy website a year ago I think that the new website like helps out a lot cause they do like take the your name and your email when you sign up to see who you are a lot of times. [P2]

With the acquisition of materials, then, we found the links (as well as separations) between DIYbio and professional biology to be further reinforced. The thing we found especially remarkable here, however, was not only the mixture of amateur and professional expertise, but also the mixing of the materials themselves. While some materials are cheap and easy to come by, others pose a challenge for DIYbio labs and thus inspire opportunistic attempts at homemade or repurposed assemblies.

Manchester DIYbio is collaborating, for instance, with the Arduino hacking group to design their own PCR machine —a thermal cycler for replicating segments of DNA. Similarly, the London biohacking group has used a combination of simple electronics and laser-cut casings to construct a gel electrophoresis box (Fig. 6.3). In addition to this homemade equipment, off-the-shelf products are also repurposed, often in simple ways. Examples include: a pressure cooker, used for sterilization and as an autoclave in Bosslab; snails from a pet store in DIYbio Manchester's breeding project; a bioartist experimenting with green tea as an antibiotic; a pet heater and thermostat from a pet store as Indie Biotech's incubator, and many others.

While such assembly and appropriation also occurs in professional settings, the DIYbio community appears to approach their interactions with materials differently. At professional labs, we found repurposing to be the easiest or only way to obtain a material. An iGem team we spent time with, for example, was relying on supermarket squid to study iridescence. Another professional biologist we spoke to uses products from local supermarkets in his lab to avoid being 'ripped off' by biotech distributors.

Despite sharing this interest in handmade and repurposed materials, the DIYbio groups appeared, uniquely, to see such practices as an end in themselves. All participants spoke of adopting others' designs and sharing their own through online forums. BiologiGarden and Indie Biotech placed a particular emphasis on creating and sharing affordable tools, with the former building a shaking incubator and the latter selling the dremelfuge and developing a new DIYbio plasmid, as discussed earlier. Numerous similar initiatives have also led to the availability of low-cost kits for purchase and assembly:

- OpenPCR—a DIY, Arduino-powered kit for performing PCR to replicate segments of DNA[43]
- Pearl Biotech—gel elecrophoresis box for hobbyists and scientists[44]
- LavaAmp—a pocket-sized hardware platform for PCR, created by biologists, engineers and philosophers[45]

These early innovations have inspired a range of ongoing projects: the 'Lightbulb PCR'—a thermal cycler made from a lightbulb, an old computer fan and an Arduino ; an iphone microscope modified with a $5 lens from Amazon ; and open source orbital shaker using Arduino and stepper motors , to name a few.

Hybrid assemblies

DIYbio's work with organic materials introduces a unique set of issues and challenges. The improvisations and combinations often result in hybrid assemblies that are different from the digital materials usually worked with in HCI. Below are four issues associated with this hybridity that emerged as especially salient in our research:

Storage

Chemical and biological samples often require specific storage conditions (temperature, light, humidity, etc.), and living organisms depend on nutrients, light cycles and other care. Also, when working on hybrid solutions, it is necessary

[43] OpenPCR, http://openpcr.org/, accessed 2013.
[44] The Pearl Blue Light Transilluminator, http://www.pearlbiotech.com/, accessed 2013
[45] LavaAmp, Pocket PCR for Pennies, http://www.lava-amp.com/, accessed 2013.

to determine how the organic materials are sensitive to paints, acrylics, FDM, and other plastics. Even with bio-friendly enclosures, there are issues of cross-contamination, not to mention questions of biosafety; as a Genspace founder, P5, emphasized, "*we didn't want to put transgenic organisms in the same fridge where people put their soda pop*."

Transport

Closely related to the above, DIYbio faces a range of transportation issues, from the physical logistics of packaging and maintaining environmental conditions in transit, to the biosecurity regulations of importing and exporting organisms. This often means hybrid assemblies require inbuilt solutions for supporting safe mobility.

Disposal

Professional organizations have infrastructures or departments dedicated to handling bio and chemical waste. As Bosslab co-founder, P2, points out, individuals often do not have access to such resources: "*there's no like straight forward answer to a lot of safety questions such as can I pour this down the drain*". Workarounds include DIY autoclaves, as well as employing professional waste disposal companies. The assemblies themselves also require ways of accessing and removing waste.

Time and uncertainty

Hardware and electronic materials are marked by precision and speed, while organic processes operate on different and often less understood timescales. For instance, it might take days to culture a cell colony, weeks to grow an algae population, or months to breed snails. Hybrid assemblies raise the challenge of coordinating the speed, accuracy and efficiencies of electronics with these far less predictable counterparts.

7.1.4 Public engagement

As a movement to 'open source science', DIYbio is fraught with initiatives to broaden participation in hands-on biology. However, by working with living organisms, DIYbio must also navigate a host of public concerns, from ethical

Figure 7.3. Gel electrophoresis box in a professional lab (left) and assembled from scratch at London Hackspace (center); OpenPCR kit for replicating DNA.

issues to legal regulations. Below, I outline a few key intersections between DIYbio and the general public.

Active participation in science

Our DIYbio participants almost unanimously shared visions of wider participation in science, ranging from more people working in DIYbio labs to individual science experiments at home. DIYbio communities host a variety of efforts to this end: Genspace runs weekly courses that cover synthetic and molecular biology; BioCurious is planning a range of classes to teach basic techniques—pipetting, PCR, etc.; and nearly all groups organize workshops with hands-on science components, such as DNA extraction and electrophoresis.

While these initiatives tend to be well-attended, they often fall short of inciting sustained participation beyond each event. The founder of BioCurious attempts to explain this:

> Some people had gone to class to take a biotech course but after the fact, all the people there were professionals in some other field… and they didn't know how like they could play with science like: 'I don't even know what the next experiment I might do is'. [P3]

As suggested by BioCurious, newcomers to DIYbio seek guidance and inspiration for projects, beyond the technical knowledge acquired through classes. Another deterrent is the form factor of lab equipment, which according to one DIYbio participant, can appear "so professional and so scary and complicated" to beginners. Thus, as a nascent field, DIYbio still lacks a body of 'hello word' examples and tutorials to afford easy entry into day-to-day practice.

Public concerns

Not surprisingly, our participants encounter varying degrees of skepticism and fear when presenting DIYbio.

> We presented DIYbio at Future Everything, a big art festival, which was great. We showed different projects we are talking about and where DIYbio is at, and it came to the questions. First question was bioterrorism, like this stuff looks terrifying. [P7]

The above quote from Manchester echoes many of the participants' experiences whereby DIYbio raised concerns of bioterrorism and safety. Consequently, DIYbio adopts several strategies to address and negotiate these issues.

First and foremost, DIYbio groups aim to shift the discussion from biosecurity (i.e., bioterrorism) to biosafety—practices that ensure safe use of organic materials outside institutional settings. For instance, numerous groups in the US (Genspace, biocurious) work in BSL1-certified (biosafety level 1) labs, while others are advised or led by professional scientists. Furthermore, after several overly-aggressive attempts to regulate DIYbio, the FBI adopted a 'community watch' approach. As part of this program, the FBI meets with DIYbio groups to discuss safe practices and mediate concerns between the labs and the general public.

In Europe, regulations around DIYbio are less established and further complicated by the ongoing debates around GMO's (Genetically Modified Organisms). Indie Biotech acquired the first individual license for working with genetically modified organisms to "*equip myself with the law and to stay on the right side of it*". Other European groups follow this philosophy, for example: "*we haven't been certified at the GMO level so we will not violate that in any way*" (BiologiGarden, P6).

Transparency

Recently, DIYbio.org initiated several events ("continental congress"), whereby representatives from local groups convened to draft a "DIYbio code that may serve as a framework for helping us achieve a vibrant, productive and safe global community of DIYbio practitioners"[46]. In addition to building consensus around best practices, the code serves an outward-facing purpose:

> Here we have a code, look at our code. This is who we are, this is what we do and furthermore when someone does something stupid or wrong or illegal then we can say look at our code, that's not DIYbio, please don't call it DIYbio. [P1]

Above, the founder of Indie Biotech explains that the code is intended to define DIYbio as a safe and ethical community, distinguishing it from people who work outside accepted practices.

In addition, our participants emphasized transparency as the key approach for addressing public concerns. Lab activities are photographed and published on blogs, websites and wikis, and day-to-day events are broadcast through social media (*e.g.*, youtube, twitter).

> I think we do that pretty well here by being absolutely transparent with everything we're trying to do. So if anyone wants to see what we're up to, just go and look at this photo stream and you'll have a pretty good sense of what's happening. [P3]

Above, the founder of Biocurious describes a public photo stream as a mechanism for sharing work with the outside world. Similarly, Bosslab has a camera that automatically uploads all images to their flickr account, as well as DIY sensors that post the temperature and status of key lab equipment to their website.

I have thus presented several interesting ways by which DIYbio relates to other stakeholders. Many initiatives invite members from the broader public to participate in science. Others serve to mediate bioethical concerns, referencing the general public as an audience. These bioethical tensions are negotiated within local DIYbio groups, the larger DIYbio.org community, and across a range of stakeholders—from law enforcement officials to members of the general public.

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[46] DIYbio Codes, http://diybio.org/codes/, Accessed 2013.

7.2 Using open source biology tools to extract, test, and visualize DNA

With DIYbio motivations, practices, and intersections in mind, I continue by presenting a more in-depth inquiry into several DIYbio tools: OpenPCR, an open source thermal cycler for replicating specific strands of DNA (*e.g.*, genes); the Pearl Blue transilluminator, a tool for visualizing the results via gel electrophoresis; and the Dremelfuge, a 3D-printed attachment for a dremel, which serves as a centrifuge. I first studied the capabilities and affordances of these DIYbio tools in a university biology laboratory and compared them against professional equipment. I then organized a workshop at a local hackspaces, whereby participants used these tools, along with several other off-the-shelf kits and parts, to test food products for genetic modifications.

7.2.1 Extracting and visualizing DNA

PCR (Polymerase Chain Reaction) is one process by which a DNA sample can be tested for a specific sequence or gene. During PCR, a mixture of DNA, primer, and DNA polymerase is cycled between three different temperature settings. The three phases are: denaturation (94-98C), at which DNA splits from a double helix into single strands; annealing (58-64C), whereby primers bond to specific sites along the single strands; and extension (68-74C), whereby polymerase compliments the DNA at target locations, synthesizing strands that are of the desired sequence. The results of PCR can be visualized with gel electrophoresis. DNA samples are loaded into a gel, and a high voltage is applied across it. Due to its slightly negative charge, DNA travels through the gel towards the positive end, with larger sequences (more base pairs) traveling at slower speeds than shorter ones. This process effectively separates out DNA segments based on their size, which can in turn be visualized by staining and illuminating the gel.

Lab-quality equipment required for extracting DNA and performing PCR (*e.g.*, centrifuges, PCR machines) can cost thousands of dollars and tend to be inaccessible to the general public. While gel electrophoresis apparatus is less expensive, the dye most commonly used to stain the gel (ethidium bromide) is a carcinogen and requires specialized handling and disposal.

OpenPCR and Pearl Biotech

OpenPCR is an open source, low-cost ($600) thermal cycler for performing PCR. OpenPCR is shipped as a kit and requires simple assembly before use. Arduino (a low-cost microcontroller) serves as its backbone, regulating a peltier heating/cooling element based on temperature data from a thermocouple sensor. Likewise, the Pearl Blue Transilluminator is also inspired by the open hardware movement, and aims to provide a safer and more affordable ($300) way to visualize electrophoresis results. The device relies on blue light transillumination and works with non-toxic "SYBR safe" DNA stains such as GelGreen[47].

7.2.2 Testing food for genetic modifications

Motivation

This research aims to understand how open source DIYbio tools might be used by members of the general public, and to uncover the design opportunities and challenges for public participation in biology. We chose GMO food testing as our example use case for several reasons. First, many off-the-shelf kits, primers, and protocols already exist for GMO analysis, thereby making food testing easier and more accessible than other types of tests. Second, the use of GMOs is a widely debated topic in the United States: the potential for GMOs to produce higher food yields and alleviate world hunger problems is often pitted against the drawbacks of heavier reliance on pesticides, structural instability of the modified organisms, un-anticipated mutations, and the risk of invasive species effecting local ecosystems. Whatever the positions held, DIY genetic testing tools can serve to initiate broader dialogues and awareness around genetically modified organisms.

Background and initial testing

Our work uses an off-the-shelf $200 kit from Carolina Biological[48] for testing food samples for CaMV 35S promoter (a sequence present in most transgenic plants). A promoter is a section of DNA that acts to 'switch on' the genes preceding it, and 35S is present in most transgenic but not naturally-occuring plants. In addition, this kit includes a control primer for tubulin, a gene present in all plant material. A positive PCR reaction for tubulin therefore establishes that DNA was extracted correctly from the food product.

Prior to organizing the workshop, our interdisciplinary team of interaction designers and biologists tested the DIYbio tools and the GMO kit in a professional laboratory over the course of four months. We experimented with several DNA extraction protocols, PCR settings, and gel staining procedures and compared results from the DIYbio tools against output from professional biology equipment. Our final PCR reaction consists of 40 cycles: 94C 20 seconds; 54C 40 seconds; 72C 60 seconds. With these settings, we were able to accurately isolate the tubulin and 35S sequence from control genetically-modified corn leaves. A base pair ladder, which consists of known-size DNA sequences, was used to determine a

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[47] http://www.carolina.com/biotechnology-electrophoresis-reagents/gel-green/217305.pr

[48] Carolina Biological Supply. http://www.carolina.com

best-fit equation for computing the size of PCR product based on the distance it travels through the gel (Table 1). Our isolated tubulin and 35S PCR results were within 7 and 6 base pairs of the expected primer lengths, respectively, which is within the acceptable margin of error in biology research (Brandner, 2002).

7.2.3 Workshop with local DIY community

Working with a local DIY community, we organized a day-long workshop whereby participants were invited to bring food products for genetic testing. The workshop was held at a local hackerspace, with 4 participants (1 female) completing the entire workshop from start to finish, and 4 others stopping by and participating in some of the procedures throughout the day. In addition to the GMO testing kit, and the DIYbio tools (OpenPCR, Pearl Blue transilluminator, and the dremel-fuge), the workshop organizers also provided an electrophoresis apparatus and several micro pipettes from the laboratory.

The workshop began with a brief overview of the steps involved in DNA extraction, PCR, and electrophoresis. Participants then extracted DNA from their food products, following printed instructions and demonstrations by the organizers. Participants were shown how to use the OpenPCR machine and load their samples. During the PCR reaction, which lasts about two hours, participants practiced loading samples into an electrophoresis gel, using food coloring for demonstration. Upon completion of the PCR, participants ran electrophoresis on their DNA samples. The gel was stained and visualized using the PearlBiotech transilluminator. An image of the gel was emailed to participants along PCR product with size calculations.

Participants brought in a range of food products for testing: an organic persimmon, organic pasta, chocolate, and cheese crackers. The electrophoresis results indicated that all participants successfully isolated DNA from their samples (based on the tubulin positive control reaction). The pasta, chocolate, and cheese cracker samples also turned out positive for the 35S promoter (GMO). The workshop was audio-recorded and photographed. This data, along with post-workshop feedback was used to synthesize three areas within our findings and we detail these below.

DIY making

Throughout the workshop, participants emphasized wanting to make all the tools involved in the protocols completely DIY. First and foremost, participants brainstormed ways to replicate the professional lab equipment we brought (gel box and pipettes) using off the shelf and cheaper components. For instance, participants discussed ways to create DIY pipettes by milling out fixed-volume indentations on a metal tray (5ul, 10ul, etc.) and then using an eye dropper to extract and apply these volumes. Likewise, participants discussed ways to build the electrophoresis apparatus from scratch using a laser cut casting tray or tupperwear. Interestingly, participants also talked about reverse-engineering the DIYbio tools themselves. Having learned the steps of PCR, for instance, participants discussed how they could create an even cheaper and more transparent PCR machine using Arduino, thermocouple, computer fan, and heating elements.

Knowledge sharing

In addition to ideating new DIY tools, the workshop also led to many instances of knowledge and expertise sharing. Our workshop relied heavily on the expertise of and feedback from professional biologists. For instance, although we provided participants with printed instructions for all the protocols, every step was also demonstrated by the workshop organizers. Participants, who had no prior experience with lab techniques such as pipetting, and no knowledge of PCR or electrophoresis, relied on demos from biologists and asked questions to complete the steps. In addition, participants also discussed and shared their own understanding of biology concepts, and researched information online during the workshop. For instance, it was not uncommon to hear participants discuss questions such as the difference between DNA and RNA, the base pairs and their role in the human genome, inherited traits, or the difference between mitochondrial and cell DNA.

Engaging with broader issues and concepts

Finally, our workshop resulted in discussions surrounding the broader scientific and socio-political issues related to genetic testing. For instance, it was not uncommon to hear our participants talk about a host of GMO-related topics, including the US legal system, which enables patenting of certain genes, or Monsanto's monopoly on some types of corn and the effects of cross-pollination with organic farms. Participants also discussed other types of food tests, for instance, the testing the genetic makeup of meat to identify its origin, in light of the recent 'fake meat' scandal[49]. In addition, several discussions addressed the use of OpenPCR more broadly, such as, for instance, running genetic tests on human DNA, or speculating on DIYbio tools given the FDA's most recent regulation of 23andme.com, a public genetic testing service for diseases and ancestry. These and other examples show how the workshop and its findings were situated within broader contexts by participants.

[49] For example, see http://www.bbc.com/news/world-asia-china-22393999

7.3 Intersections and seams

Thus far, I have presented several strands of investigation into the DIYbio movement, including a study of its practices, as well as my work with several DIYbio platforms in a professional lab and during a community workshop. Findings from this research suggest an array of complex intersections: i) DIYbio draws on existing hacker practices and values while also collaborating with professionals; ii) the materials are often hybrid assemblies of living organisms and digital technologies; and iii) DIYbio references the general public as active participants and a concerned audience.

In this section, I want to give thought to a more general but, I hope, still constructive way of orienting to the area—with the intention of opening up opportunities for HCI. The framing we found particularly useful has been one of designing across seams, those points at which different materials, practices, categories, etc., intersect, sometimes in unexpected ways. The biology-machine intersection is itself such a seam, of course. Yet there are other compelling juxtapositions if we consider the reported bio-electronic materials, such as the Arduino-controlled PCR machine for replicating DNA or a shaking incubator that uses servos to culture living organisms. On a higher level, DIYbio operates at the fringes of professional science and hacker subcultures, while also intersecting with the general public.

To explore the intersections emergent in our research, we constructed three design exercises we see as operating at the seams. All three prototypes are fully-functional devices, built using the Gadgeteer .NET platform[50] and FDM 3D-printed enclosures. We present these artifacts as design probes to prompt critical reflection on the role HCI might play across some of DIYbio's complex intersections. This approach is similar to the previous chapter's, as it builds on prior work in HCI where the construction of artifacts productively raises questions and opens new design opportunities for future work (*e.g.*, Gaver et al., 2008; Sengers et al., 2002). It's worth reiterating that the point here is not to present our prototypes as solutions to specific DIYbio problems, but instead, as examples of how working at the seams can be fruitful for HCI.

7.3.1 Exercise 1: DIYbio and professional biology

DIYbio has intentionally positioned itself as a movement outside of and in some ways opposed to professional biology. From its motivations (to 'open-source' science or unsettle institutional power structures), to the aesthetics of tinkering

[50] .Net Gadgeteer. http://research.microsoft.com/en-us/projects/gadgeteer/

with organic materials and its close associations with existing hackspaces, DIYbio's agenda is not one of academic research. At the same time, the lack of 'how-to' examples for beginners and the complexity of the science, its equipment and surrounding ethical issues necessitate biologists to remain at the core of DIYbio. Our workshop, for instance, relied on input from professional biologists, as well as inspiring participants to research and share biology information independently.

This tension—of being set apart yet being closely in touch with professionals—inspired our first design exploration. Currently, communication between practitioners with varying degrees of expertise is mediated by online forums and blogs, or through advisory boards as in the case of Genspace and Manchester. To open this space beyond computer-mediated or in-person interaction, we developed a screen-based, wifi-enabled device that looks not unlike a petri dish (Fig. 6.4). In our exercise, it was programmed to display messages from the DIYbio Manchester's mailing list to be viewed by professional or DIY biologists in remote laboratories. Opening the lid and tilting the "petri dish" toward oneself activates the screen, and tilting it left or right advances the content backward or forward.

On the face of it, this design object explores something that probably isn't a major problem for biology practitioners; after all, most are astute internet users. However, the design and subsequent discussions prompted us to consider location, cultural practices, and form factor for communicating information within a biology lab (whether that be someone's garage or a traditional laboratory). Inspired by the physical aspects of labwork, the form factor of our device mimics practices of examining a sample in a petri dish. How might form factors influence professional and DIY labs to critically examine each other, and what kinds of new benefits or complications could arise? In this way, the device also prompted

Figure 7.4. Design exercise 1, interactive petri dish display.

questions about boundaries between the wider DIYbio community, the physically delimited professional and DIY labs and the work within them. For instance, how can information be shared more fluidly across physical settings while also sensitively supporting cultural differences between professionals and hobbyists?

7.3.2 Exercise 2: DIYbio and the general public

The second exercise explores relationships between DIYbio and the broader public. Again, this seam is fraught with tensions: DIYbio encourages people to participate in 'hands on science' through workshops, classes, etc., while also navigating the many public concerns regarding its practices. Its outward-facing efforts, from a code of ethics to mechanisms that make lab work more transparent, publically address questions of safety and ethics. Moreover, DIYbio offers new tools and platforms for engaging members of the general public in broader sociopolitical discourse. Our workshop for instance, which revolved around testing food products for GMO's, led participants to discuss genetic testing within broader contexts.

With transparency as a key value for DIYbio, we designed a GPS/SMS-enabled touchscreen device, not unlike a microscope, for viewing and sharing organic processes (Fig. 6.5). A petri dish can be placed on the device, and a camera mounted above magnifies and displays its contents on the screen. Images can also be stored on an SD card or shared via SMS along with the device's GPS location. In our example application, images are saved every ten minutes and can be viewed as a time-lapse video of the biological process. The record and play functionality is invoked through a menu on the device's touch screen.

In constructing this artifact, we uncovered a range of design opportunities at the intersection of DIYbio and surrounding public issues. As open source biology tools continue to become more widely available, the socio-political implications remain to be explored. On one hand, this suggests that low-cost genetic testing can enable new ways of sensing and understanding information about organic materials such

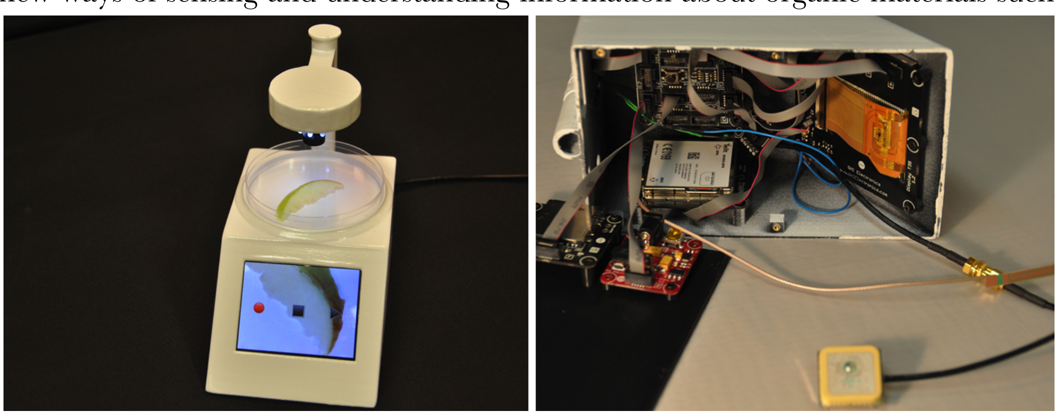

Figure 7.5. Design exercise 2, GPS/SMS-enabled microscope.

as foods, plants, animals, or human beings. For instance, access to GMO testing might lead to transparency within the food system, while DIY tools for testing human DNA might support different forms of healthcare. With these developments, genetic data access and sharing present another rich design space. For example, future systems can enable practitioners to share genetic test results, such as the ones from our workshop, with relevant stakeholder groups such as policy makers, activists, or members of the general public. In addition, design can explore the ethical implications, safety concerns, and the unintended consequences of public participation in science.

7.3.3 Exercise 3: Hybrid materials

The final exercise focuses on the hybridity of DIYbio materials. Common electronics—Arduino, sensors, servo motors, etc.—are combined with more professional lab equipment to culture, study or modify organic specimens such as e. coli, c. elegans, zebrafish or snails. The underlying seam—between living organisms and digital technologies—results in imaginative, innovative and sometimes strange workarounds across issues such as storage, disposal, time and uncertainty. For example, we presented how during our workshop, participants ideated ways to make the biology tools more transparent, affordable and accessible. Involvement with DIYbio materials and procedures thereby served as an inspiration point for innovating at the intersection of organic and digital.

To gain broader insights into working with living organisms, we designed an interactive device for viewing bioluminescent algae (pyrocystis fusiformis). These algae emit a blue-green light when mechanically agitated (*e.g.*, shaken), but require a resting state between each stimulus for the shaking to have noticeable effect. Our device is thus made up of a glass vile of algae attached to a servomotor, all encased in a dark container with a small hole for viewing (Fig. 6.6). An external trigger (for the purposes of this exercise, a button) oscillates the servomotor, shaking the algae. After each actuation, luminescence is measured with a light sensor that has been calibrated for blue/green wavelengths and presented on a

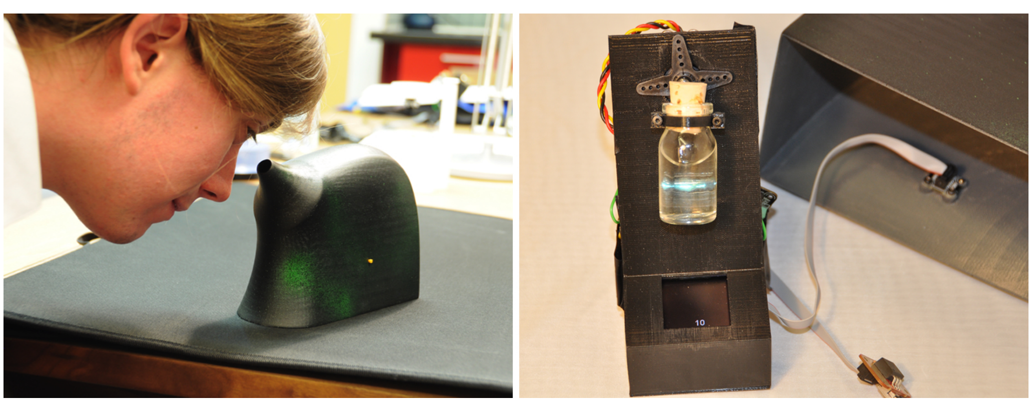

Figure 7.6. Design exercise 3, bioluminescent algae shaker.

small display below the vial.

Despite its simplicity, we found this prototype to raise some unexpected issues. For instance, the delay required between shaking the algae led us to build a counter into the display to indicate when the device is ready to be used. Also, since the algae depend on a 24-hour light/darkness cycle, after each demo, specimens had to be stored in a dark place with timer-controlled lights. The need to consider these issues illustrates that the qualities of living organisms (time, storage, care, etc.) demand, perhaps predictably, very different approaches to interactive system design. In our exercise, we wondered how new designs could exploit the delay between actuation and the somewhat theatrical quality of having to peer into a darkened container to view a dispersed luminescence. More generally, we were left to ask, might there be benefits to designing technologies that mimic living qualities, such as being slower, less predictable and more reliant on our care?

By operating at the intersection of digital and organic, and at the seams across professional, amateur, and public, the DIYbio movement might offer valuable insights. At the very least, our design exercise suggests several direct points of engagement for HCI, for instance: bio-electronic "hello world" examples for 'playing with bio', such as our simple algae device; electronic platforms that can be more easily interfaced with living organisms (*e.g.*, Arduino shields that maintain specific light and temperature conditions for culturing certain organisms); technologies that support "sketching in bio", similar to Sketching in Hardware[51], for quick prototyping of bio-electronic systems; as well as new infrastructures for working with organic materials, including assemblies for storage and transport, and tools that support safe disposal.

7.4 Conclusion

In this chapter, I have outlined findings from our study of DIYbio communities around the world, as well as my investigation of open source biology tools and their use in a workshop with a local DIY community. Returning to my over-arching framing of citizen science initiatives as publics, there are several ways in which DIYbio movements present a unique point of reflection for HCI. I presented DIYbio as a growing community of individuals and groups that coalesce around tinkering and experimenting with biology outside professional labs. At the heart of this effort are concerns regarding open access to biology. Emerging publics of hobbyists, artists, and scientists explore this issue by innovating creative tools and materials for at-home experimentation, sharing expert and amateur knowledge, conducting public outreach events, or addressing

[51] http://sketching-in-hardware.com/

biology problems such as genetic health testing, bio-fuels, or food production with DIY tools.

These unique practices result in complex intersections across stakeholders, materials and concerns. Drawing on the *seamful* computing framework of Chalmers and Galani (2004), I focused on three *seams* that emerged from our research: i) DIYbio and professional biology; ii) DIYbio and the general public; and iii) hybrid materials of living organisms and digital technologies. To reflect on HCI's role across these seams, I discussed design exercises that explore three areas for future research: *internal collaboration tools* within the DIYbio and professional community; *mechanisms for external communication* with stakeholders from the general public; and *bio-electronic assemblies* of organic and digital materials.

More broadly, I hoped to show that the particular properties of biology, and its convergence with electronics and DIY practices, invite questions for HCI around generative hybrids, and seams or intersections. A specific concern for intersections, especially in DIYbio, offers a way to start thinking openly about new design possibilities. For instance, the various ways of seeing the divisions between DIYbio, professional biology, and the public offer opportunities for designing at these intersections. Likewise, the points of intersection between the biological and electronic open up opportunities for imagining new hybrid technologies. Our design exercises at the seams offer initial and modest attempts at designing in and for these junctures. Each exercise serves to suggest implications for interactive systems at the seams of biology, computation, and public engagement.

8 Public participation in personal genetics

In the previous Chapter, I examined the niche but growing DIYbio community working to make biology practice more accessible to everyone. Here, I explore larger-scale services and platforms that are, in some ways, aligned with these efforts by engaging members of the general population with personal genetics. Indeed, since the completion of the Human Genome Project[52] an international research effort that mapped the human DNA in its entirety in 2003, genetic research and its underlying technologies have advanced in radically new and unexpected ways. The cost of genetic sequencing, for instance, has decreased exponentially over the past decade. Doctors, start-ups, public services, and even home-made equipment are enabling members of the general public to participate in genetic testing. These advances parallel those of more traditional citizen science research, both in terms of lower-cost sensing (genetic sequencing), as well as increased computational power for processing genetic information, and social media tools for supporting the emerging communities of participants.

With these developments, people are increasingly able to explore their personal genome, often without relying on trained scientists as intermediaries. This results in a citizen science shift from people 'as sensors'—*i.e.*, gathering information about their external environments—to communities who collect, make sense of, and act on information embedded in their own bodies. Participation in genetics is thus often motivated by and brings about a host of new concerns, from discovering personal and intimate information about oneself to understanding broader patterns in human migrations and evolution. Little is known within HCI research about the challenges and practices in this space: how do people interact with the underlying scientific information; how does their understanding of personal genetics influence their daily lives; and how can the results of this participation be made more valuable to professionals and the public at large?

To answer these questions, this chapter examines the practices and motivations of contributors to 23andMe[53], a low-cost ($99), online service and community for personal genetic testing. 23andMe users can track a range of genetic results—from one's ability to taste bitter flavors, to hereditary illnesses such as Parkinson's disease (Fig. 8.1)—and learn about one's genetic ancestors. In addition, the site

[52] National Human Genome Research Institute. All about the Human Genome Project. http://www.genome.gov/

[53] 23andMe. http://23andme.com

offers a range of biology and genetics tutorials and general scientific information. The site serves as a portal for personal and family health information, as well as an educational tool, and a mechanism for contributing to science.

While the architecture and interfaces of 23andMe may be familiar to HCI, the content supports a new type of online community—one where the information shared and acted upon is rooted in personal DNA rather than knowledge, skills, or common interests. Communities such as 23andMe are giving rise to a new form of biological citizenship (Rose, 2005) in which the meaning of identity, community, and family is renegotiated by genetics. Crowdsourcing and interpreting genetic data are not merely new forms of scientific participation. These emerging practices bring our genetic makeup and its broader connotations—curiosity, hope, fear—to the forefront of today's political and ethical arena.

This chapter reveals how 23andMe participants come to understand and make sense of their genetic information, how this information is contextualized and acted upon, and how it serves to further scientific knowledge production. The findings reveal i) why participants joined 23andMe; ii) how they contextualized the data within their lives and environments; iii) how they critiqued and evaluated the underlying research; and iv) their reflections on the broader implications of genetic testing. I conclude by discussing how these practices are aligned with Rose et al.'s (2005) concept of biological citizenship. I also draw parallels between the mechanisms by which groups coalesce around genetic research and the practices of other citizen science publics I discussed earlier in my dissertation. I conclude with three opportunity areas for supporting biocitizen publics through HCI: platforms for gathering genetic data and experiential knowledge; tools that support public critique of scientific research; and ways that personal genetics communities can more broadly influence professional research.

NAME	CONFIDENCE ▲	OUTCOME
Alcohol Flush Reaction	★★★★	Does Not Flush
Bitter Taste Perception	★★★★	Can Taste
Earwax Type	★★★★	Wet
Eye Color	★★★★	Likely Blue
Hair Curl	★★★★	Straighter Hair on Average
Lactose Intolerance	★★★★	Likely Tolerant
Malaria Resistance (Duffy Antigen)	★★★★	Not Resistant
Muscle Performance	★★★★	Likely Sprinter
Non-ABO Blood Groups	★★★★	See Report
Norovirus Resistance	★★★★	Not Resistant
Resistance to HIV/AIDS	★★★★	Not Resistant
Smoking Behavior	★★★★	If a Smoker, Likely to Smoke More
Male Pattern Baldness ♂	★★★★	Not Applicable
Adiponectin Levels	★★★	See Report

Figure 8.1. Sample 23andMe genetic traits.

8.1 About 23andMe

Founded by Linda Avey and Anne Wojcicki in 2006, 23andMe is a biotechnology startup aimed at providing low-cost, rapid genetic testing. The service offers "a comprehensive genetic scan of a subset of the SNPs (single nucleotide polymorphisms, or DNA variations) in your genome which correspond to the SNP data being studied by the research community"[54]. 23andMe works as follows: 1) a user can order a 'spit kit' online, which arrives a week later **(**Fig. 8.2**);** 2) the kit is used to collect and preserve the participant's saliva sample, and is mailed back to 23andMe; 3) after a 4-6 week processing period, the results can be viewed and shared from the user's online account.

The health results profile over 240 conditions, ranging from multiple sclerosis, to alzheimer's disease, cystic fibrosis, sarcoma, or Keloid, as well as traits such as alcohol flush reaction, hair curl type, lactose intolerance, smoking behavior, biological aging, or photic sneeze reflex, and drug response—sensitivity to coumadin, phenytoin, warfarin and others. Ancestry results include maternal and paternal line haplogroups (genetic populations that share a common ancestor), overall composition broken down by geographic region, and percentage of neanderthal DNA. The site also provides a range of social networking tools: relative finder, which connects users based on shared DNA; forums, whereby users can discuss topics such as health, ancestry, specific haplogroups, neanderthal ancestry, alzheimers diesease, or general questions about the 23andMe service. Users can also build and share their family tree, trace traits across generations of different family members, or compare personal DNA to other 23andMe users.

8.1.1 A platform for citizen-driven genetic research

23andMe links its results with corresponding academic publications, enabling

Figure 8.2. 23andMe spit kit.

[54] 23andMe. https://www.23andMe.com/. Recently (after this work was completed) the FDA ordered that 23andMe stop displaying health results to participants.

users to learn how the findings were produced and 23andMe's confidence in its data. Some 23andMe results are improved through surveys and questionnaires on the site. These cover ancestral and health history, and personal traits such as computing one's empathy quotient, determining if one's personality is planned or spontaneous, or smoking behavior. The site also provides surveys that lead to discoveries—helping scientists identify genetic variants that are associated with traits such as dimpled chin, freckling, or earlobe type.

In addition, 23andMe invites community members to propose their own research projects. The site aims to "involve our customers in research as collaborators, advisers and contributors by conducting studies that correlate their responses to online surveys with their genetic data. The idea is to enable large studies that would be infeasible using current methods, which typically involve recruiting patients through physicians' practices and other means". Members can submit research proposals, which are evaluated by 23andMe internal and external committees. Upon approval, members can design studies, recruit respondents, and analyze the data through 23andMe. Ongoing projects aim to identify SNP's that might be associated with specific traits, including Parkinston's disease, sarcoma and Alzheimer's. 23andMe therefore serves as platform for collecting and analyzing genetic data.

8.2 Research methods

We began our research by reviewing and coding public 23andMe forum posts. Our research covers both the initial posts and the corresponding responses within 150 threads from Labs, Measures of Intelligence, Health, Relative Finder, and Hereditary forum topics. We identified 238 themes, which were affinity diagrammed into topical categories. These high-level groupings served as focal points for our in-depth qualitative study of 23andMe users. The study followed six individuals as they joined 23andMe and interacted with the service over the course of 3 months. Participants completed initial semi-structured interviews about their motivations for joining 23andMe, prior knowledge of genetic testing, as well as their personal health, family history, personality and intelligence. After the initial interview, participants signed up for the 23andMe service with private accounts (that are not accessible to the researchers) and completed the spit kits on their own. Participants attended follow-up interviews when their data became available online, probing their reactions to and understanding of the results, whether or not their expectations were met, and how the information might impact their lives in the future.

Data from the first two interviews, along with the themes derived from the forums, was synthesized into two co-design activities for our third set of interviews. These final interviews were conducted about a month after participants' data was first made available on 23andMe, probing how the service affected participants' lives over the past month, and asking them to complete the co-design activities. Participants were compensated $10 per hour for their time during the interviews, and reimbursed for the 23andMe service. Data from the interviews was transcribed and coded to themes.

8.2.1 About the participants

Participants were recruited with flyers posted at local bulletin boards, coffee shops, gyms, and restaurants, and pre-screened to ensure a range of ages, backgrounds, and family situations, as well as a gender balance. Our study included 6 participants (ages 24-64, 3 male): five completed all interviews, and one completed only the first two due to a delay caused by a 23andMe DNA processing error. Participants' occupations included a massage therapist, an engineer, a federal contractor, a musician, a project assistant, and a retired music teacher. None of the participants had a genetics or related background, and only P1 had used genetic testing before the study to find out her ancestry. I continue by detailing our findings across four themes: i) motivations for joining 23andMe; ii) contextualizing 23andMe data; iii) validating 23andMe results; and iv) the broader implications of genetic testing.

8.3 Motivations for joining 23andMe

Participants and forum contributors cited health, ancestry, identity, and community as key motivations for joining 23andMe. What often set these apart from motivations of other citizen science communities is the highly personal and intimate nature of the information being sought after.

8.3.1 Health

All participants described themselves as health conscious, and linked health with a combination of environmental, lifestyle, and genetic factors. Three of the participants were interested in 23andMe primarily for health reasons. P1, for instance, wanted to learn if breast cancer, which ran in her family, was caused by genetics:

> I'd love to see the health side of my background. Both my grandmothers had breast cancer. My maternal grandmother died from it my paternal grandmother had them removed and she survived. But none of my aunts have had it. So I wonder if it was genetic or if it was something environmental. (P1)

Similarly, P2 wanted to learn about drug responses, and whether they were linked with his ethnicity. P1, P2 and P6 were interested in '*actionable information*' to reduce the risks of developing genetic diseases. It's important to note, however, that two of the participants, P4 and P5, were more skeptical of the role their genes play in their health.

> I just think that we have so much more control over our health than geneticists and most people lead you to believe… I just wouldn't be too concerned about anything that indicated like oh you have an elevated risk for this cancer or that or this because I just feel like I know that the way I live my life has way more to do with it than just some genes. (P4)

The above excerpt shows how P4 believes that her lifestyle, rather than genetics, is what influences her health. P4 and P5 both stated that they would not be concerned about their health risks on 23andMe.

8.3.2 Ancestry

All six participants were interested in their ancestry, and had their family histories passed down to them by word of mouth, and/or written records such as birth and marriage certificates, as well as comprehensive written family trees and genealogies. To varying degrees, all participants described mysteries or disagreements about their pasts, and were hoping to learn more through 23andMe:

> I'd like to know whether what I've been told by relatives you know how accurate it is 'cause I know they traced the family tree of my mother's mother's mother's family but the rest of it you kinda go by family tales. (P5)

The unknowns included inconsistencies in documents such as birth certificates, as well as questions about specific family members' backgrounds. Participants also wanted to rectify disagreements about the ethnic and geographic composition of their ancestors, such as, for instance "*rumors about Chinese ancestors*" (P2) or whether or not her paternal side, which has been believed to be pure English, has any "*Irish blood*" (P5). Moreover, participants were interested in early migrations ("*information about where my ancestors migrated from*", P2; "*what different migrations of people out of Africa you're most closely related to and that really interests me*", P4). These motivations were also reflected by the Ancestry and Paternal/Maternal Line forum postings (*e.g.*, "*I'm adopted (the reason why I joined 23andMe) so I really don't know much about my family or relatives*."[55]).

8.3.3 Personal identity

While health and ancestry were cited as the primary motivations, participants also tended to link genetic information with ideas about personal identity.

> Ancestry is part of personal identity and I want to know who I am… I think that in order to best know where you're going it's good to know like where you came from. (P2)

> I like exploring existence and just the mind and body and just curious. Just understanding more and more about myself. (P6)

[55] https://www.23andMe.com/you/community/thread/15124/

I'm just interested in finding out about my genetic code and what part of that plays into who I actually am. (P3)

In the excerpts above, participants express a desire to learn more about themselves through the use of 23andMe. These comments highlight the ways participants view their genes as playing a key role in who they are. To different extents, this idea was reflected by all participants, who discussed 23andMe as a resource to learn more about oneself.

8.3.4 Community and connectedness

Finally, several participants also highlighted the value of 23andMe as a community tool. For example, P3 was interested in the "*less clinical*" aspects of genetic testing:

> You can like see different people in the community and see who you're related to and it seems less clinical I guess than if I were to just test for diseases and be like oh I'm a carrier for this.

Similarly, P4 suggested that the service might be "*fostering a sense of community and interconnectedness within human beings*". Forum posts, especially in the Community category, reflected this idea as well:

> Who would ever join this thread if they didn't want to find out something about people who are genetically similar to them, especially when they have rare, or rare-ish combinations? That's why I joined 23andMe...[56]

Interestingly, individual genes were often used as "pivots" on which to find other users that had similar traits or conditions (*e.g.*, "*Is There Anyone Else with 2Copies of the Gene for Intelligence?*"). However, these connections were not motivated by forming social bonds such as making friends, but rather for informational reasons (*e.g.*, to learn about the experiences, backgrounds, and health problems of those with similar traits, disease risks, or ancestry).

To summarize, participants and forum contributors cited a host of personal and intimate reasons for joining 23andMe including mitigating personal health risks, rectifying discrepancies in family histories, reflecting on personal identity, and learning from other 23andMe users.

8.4 Contextualizing and linking genetic data

Participants expressed a range of initial reactions to their data, from feeling like they won a '*genetic lottery*' (P1) and describing the information as '*futuristic*' and '*cool*' (P3, P6), to being somewhat disappointed with a lack of specificity in the ancestry data (P2, P4). Over time, participants tended to link their genetic data with various aspects of their lives, as well as environmental factors, and cultural and

[56] https://www.23andMe.com/you/community/thread/12766/

historic knowledge. These links often served to determine causality—to explain why or how participants came to be who they are, and to make sense of their surrounding world. The links also served to alter lifestyle and behavior, as well as predict implications for future relationships, and generations. I detail several of these connections and their implications below.

8.4.1 Past experiences

The study participants, along with the forum contributors, compared 23andMe results with personal experiences, inferring the genetic data to be correct only when these matched. For example, P1's odds of post-operative illness were consistent with her prior experience with anesthesia and her non-verbal intelligence results on 23andMe matched earlier SAT test scores. Similarly, P2 linked his odds of developing keloids with past injuries, while P3 associated his genetic 'inability to taste bitter flavors' with his preference for bitter foods such as coffee or beer. Posts across the Health forums expressed similar connections (*e.g.*, "*My 23andMe health risks does state I have a high risk for asthma… I am sensitive to certain things like wood smoke, some flower fragrances and some perfumes*."[57]).

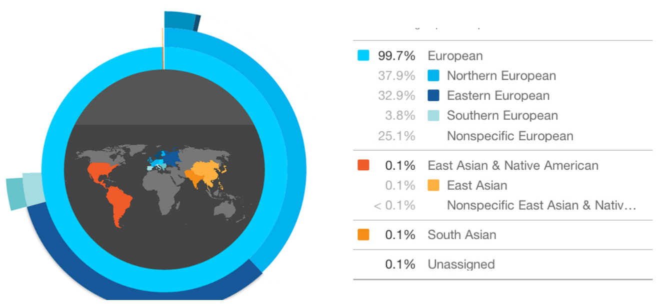

Figure 8.3. 23andMe ancestry DNA visualization.

8.4.2 Background and family history

Similar to drawing on their personal experiences, 23andMe users also linked their genetic data (Fig. 8.3) with what they knew of their family histories and backgrounds, and in many cases, used these comparisons to validate the 23andMe results. It was not uncommon to observe participants cross-referencing their high-risk traits with specific family members who experienced those conditions (*e.g.*, "*I know people in my family who've had a lot of these so it seems like to match up*", P3). For instance, P4 noted that intolerance of cumadin and eye degenration, which 23andMe showed her at risk for, run in her family; while P1 associated her Eastern European background, as shown on 23andMe me, her dad's side "*because*

[57] https://www.23andMe.com/you/community/thread/8777/

there's Lithuanian and some other things over there". These findings were consistent with our forum analysis, which showed other examples of traits being linked with family histories (*e.g.*, "*I am a carrier (for hemochromatosis) and my Aunt died from the disease*."[58]; "*I've found synasthesia to be genetically linked on the maternal side of my family*.[59]).

8.4.3 Resolving unknowns about the past

In addition to associating 23andMe data with known family facts, participants also tried to use the service to resolve inconsistencies and unknowns. For instance, P1 speculated that her surprising Ashkenazi heritage, as shown by 23andMe, might explain a mysterious name change in the family. Likewise, forum posts included links between ancestry results and specific family members.

> *It* [the results] *may clear up the question of her race. I have found Jacob Cassell, which may confirm the Cherokee rumor in my family.*[60]

However, other attempts to explain background questions were less successful, especially in cases when 23andMe results did not provide enough detail. P2, for instance, could not infer whether his background included Chinese ancestry, because his heritage was shown broadly as "South East Asian" on 23andMe. Similarly, P5 could not determine if her paternal side contained Irish heritage based on the "European" category. Moreover, all female participants were disappointed with the fact that the service could not profile their paternal side.

8.4.4 Lifestyle and behavior changes

Five of the participants also linked 23andMe results with changes in day-to-day behaviors. For example, P2, who was shown to have a high chance of blood clots by 23andMe, planned to get an exercise ball and walk more; P3 noted that his increased risk of developing a heart condition, as suggested by 23andMe, "*reminds me that I should be healthy… eat healthy and it can be avoided*". P6 also reconsidered his diet and exercise based on his inherited traits:

> Like the fact that I'm likely *[lactose]* intolerant—that made me interested in realizing maybe I should stay away from milk cause I've noticed if I drink a lot of milk I get a little stuffy. The muscle type, that I'm likely not a sprinter that made me think about how I should exercise.

Forum threads also showed a host of similar examples, whereby results influenced participants' behaviors:

> Since the 23 & Me results I am reducing my fat intake.[61]

> My take-away from this is: stop eating meat. It has a high correlation with stomach cancer and if you are potentially at a higher risk it is in your best interest on so many levels to minimize risk.[62]

[58] https://www.23andMe.com/you/community/thread/563/

[59] https://www.23andMe.com/you/community/thread/14056/

[60] https://www.23andMe.com/you/community/thread/18896/

[61] https://www.23andMe.com/you/community/thread/10116/

It is important to note, however, that although the majority of our participants and many forum posts linked genetic risks with lifestyle changes, P4 was less concerned about the role her genes play in her health. Throughout the interviews, P4 emphasized that environmental factors influence her disease risks more than her genes do, and she was therefore not planning to make any changes based on the 23andMe results.

8.4.5 Cultural and historical context

Finally, participants also contextualized their genetic information within their broader understandings of history, culture, religion, and evolution. For example, historical knowledge was used to speculate on and explain unexpected 23andMe results:

> So it says 0.7% South Asian, which I can see that because you know just historically there's a lot of trade between south Asia and the Philippines there's a kingdom down there. (P2)

In the above excerpt, P2 notes that his South Asian heritage, as shown on 23andMe, could be explained by ancient trade routes. Similarly, P4 associates her surprising Balkan lineage with a broader view of fluidity across cultures:

> It did show that I had some Balkan ancestry… and it's interesting because it kinda goes to show how you know we think of there being some kind of stability with like ethnic groups of people but of course all kinds of people have been migrating all over for a really really long time… there's just a lot more fluidity.

Interestingly, some of the results were also associated with cultural stereotypes (*e.g.*, "*I don't have the alcohol flush reaction, which is usually I thought was mostly Asian people who have that*", P3; "*I'm an Asian that's bad at math*", P2, based on measures of intelligence results).

Evolution

Similar to placing genetic results in a historical or cultural context, participants and forum contributors also linked genetic information with their ideas about evolution. P5 speculated about how evolution might have played a role in creating the gene that prevents people from tasting cilantro, while forum posts hypothesized about evolutionary causes of certain genetic traits or mixing with Neanderthal DNA (Fig. 8.4):

> Is it something that millennia ago that people were in a certain area and it was lifesaving to them to—you do not touch the cilantro. (P5)

> I have seen some articles that suggest such beliefs have significant survival value and would be favored by natural selection.[63]

[62] https://www.23andMe.com/you/community/thread/9664/

[63] https://www.23andMe.com/you/community/thread/538/

I have 3.1% Neanderthal genes, which puts me in the top 98th percentile of all humans. Since evolutionary biologists and geneticists believe the Neanderthal and modern human mixing occurred in southern Europe, that could explain it.[64]

These excerpts exemplify how 23andMe users linked genetic test results with potential evolutionary causes.

To summarize, this section highlighted how 23andMe results were contextualized within and linked to users' environments, lifestyles, family backgrounds, and broader cultural and historical knowledge.

8.5 Making sense of perceived inaccuracies

While contextualizing 23andMe data within aspects of their lives, participants and forum contributors found instances where they did not agree with the results—from traits such as eye color, photic sneeze reflex, or smoking behavior, to their ancestry such as haplogroup information that did not reflect their country of origin. Although most participants (5 out of 6) appreciated being able to see the studies 23andMe drew upon to present the data, they also tended to cross-check information with other genetic testing services, as well as sources such as Wikipedia, Mayoclinic, WebMD, and friends who they considered to be experts. Oftentimes, these inquiries led users to question, debate, or refute scientific information. Many factors—from environmental influences, to study limitations and biases—were drawn upon to determine whether the genetic data was reliable. Below, we detail how participants made sense of and interpreted discrepancies between their perceptions of themselves and their external world, and the genetic data that reflected the invisible information within their bodies.

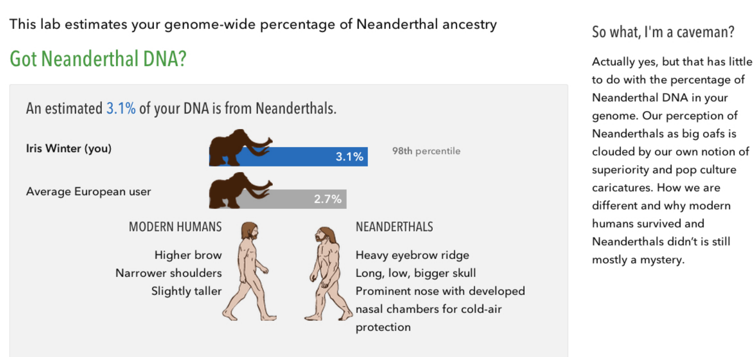

Figure 8.4. 23andMe Neanderthal DNA visualization.

[64] https://www.23andMe.com/you/community/thread/11378/

8.5.1 Nature vs. nurture

All of our participants, as well many of the forum posts we analyzed, discussed genetic testing as an indicator that has a degree of uncertainty. It was not uncommon to hear our participants refer to 23andMe traits and conditions as a "propensities", or "not definites". To varying degrees, all participants acknowledged 23andMe results as predispositions rather than guarantees (*e.g.*, "*whether they're activated has to do with a lot of factors*" P4). Participants and forum posters emphasized the role that environment and lifestyle plays in gene expression:

> This risk is not taking into account me, but only my genes. (P3)
>
> This [risk] doesn't take into account that I live in an industrialized city so I think it's a lot more immediate. This could say whatever you want but it won't know if you're extremely obese. (P6)
>
> It's always going to be a complex interplay of nature and nurture; genetic factors or predispositions probably (at least IMO) going hand in hand with environmental / cultural factors, *individual* predispositions, etc.[65]

These excepts show that, while in many cases, participants did not doubt the accuracy of the genetic tests per say, they attributed inaccuracies in their results to the influences of environmental and lifestyle factors.

8.5.2 Small datasets and preliminary research

In other cases, 23andMe users critiqued the results for being based on small (inconclusive) datasets. It was not uncommon to hear participants refer to 23andMe results as based on "*preliminary research*" (P3), or findings that are constantly changing based on new or incoming data (P1).

> There's more studies more research going on so I guess within the framework of the limited knowledge that we have now and our understanding of things now as a snapshot I guess I trust this as much as you can *[trust]* what we know now. (P2)

Above, P2 notes that 23andMe results are dependent on '*what we know now*', and may change as new data comes in. P6 and P3 also pointed out that 23andMe tests for a small subset of genetic mutations. For instance, P3 commented that the service "*only tests for 3 of 100s of possible mutations you might have in the BRCA* [breast cancer] *gene*"; while P6 also critiqued the 23andMe service for not taking into account how different genes might interact with each other.

8.5.3 Limitations and biases of supporting studies

In some cases, participants and forum contributors also identified limitations and biases in the underlying research. It is important to note that even prior to joining 23andMe, all participants expressed a skepticism towards scientific publications—from questioning data that is "*constantly changing*" (P2), to suggesting that findings

[65] https://www.23andMe.com/you/community/thread/15866/

may be influenced by corporations, researchers' "*pre-conceived ideas*" (P4), or financial and political motivations (P5). Given participants' initial skepticism towards scientific research, it is not surprising that they also identified limitations in studies cited by 23andMe. Most commonly, they noted that that the related studies did not apply to their gender, ethnicity, or age group (*e.g.*, "*this health risk assumes I'm European and of a different age*", P3; "*maybe if I was that group it would be accurate*", P2). Furthermore, participants also pointed out that many of the sample sizes were too small (*e.g.*, a study of 139 people), or had un-accounted variables (*e.g.* "*who are you studying will skew results*", P4).

In addition, several forum discussions expressed concerns over potential biases in the underlying research.

> Most science has become politicized nowadays, and in many fields it is rare for a person to strive for the truth ahead of getting published, getting tenure, or other renown.[66]

> I think the test has a major flaw in that all the people are white… So would it not make sense that white people would do better on this test than Asians, Mexicans or African-Americans?[67]

The two excerpts above illustrate potential research biases that were of concern to 23andMe users: ulterior political or financial motives of the underlying studies, and racial bias.

8.5.4 Inaccurate 23andMe survey responses

Finally, participants and forum contributors questioned the accuracy of some of the 23andMe results that were based on the site's surveys. For instance, P5 noted that she guessed her survey answers when she could not remember her family history, and was worried that others might be doing the same, thereby skewing the data. Moreover, P3 pointed out that there was no mechanism for changing one's survey responses if they were accidentally entered incorrectly. Several forum posts expressed similar concerns (*e.g.*, "*I really have to question the effectiveness of some of their* [23andMe] *research questionnaires*"[68]).

To summarize, this section outlined several ways by which participants and forum contributors made sense of instances when their 23andMe results did not match with what they believed to be true about themselves. Among the discussed factors were the influence of environment and lifestyle over genetics, as well as lack of data, limitations of supporting studies, and inaccuracies in 23andMe survey responses.

[66] https://www.23andMe.com/you/community/thread/538/
[67] https://www.23andMe.com/you/community/thread/13697
[68] https://www.23andMe.com/you/community/thread/8139/

8.6 Broader implications of genetic testing

Finally, our forum analysis and discussions with participants revealed ways that 23andMe users reflected on the broader implications of genetics. Below, I detail users' speculations about potential positive and negative consequences, and new ways of seeing that might emerge as genetic testing becomes more widespread.

8.6.1 Potential positive consequences

All participants emphasized that genetic testing poses unprecedented opportunities for healthcare.

> I think it just would be empowerment for people to be able to watch out for their own health. I think it would be on a societal basis … I would think people would take a little better care of themselves or at least would know what to watch out for. (P1)

Above, P1 highlights how access to genetic testing might empower people to mitigate disease risks and/or take better care of personal health. To varying degrees, all participants also highlighted opportunities for improved preventative care and diagnostics, and drugs being designed to suit individuals based on their genes. Participants also pointed out that services such as 23andMe could '*advance scientific knowledge*' for researchers and the general public (P1, P2), or serve as an *'educational tool'* to show how '*humanity is evolving'* (P4).

More broadly, several participants also commented on the implications of large communities forming around shared ideas rooted in genetics.

> It brings people together with all this medical information already tied to them… so it's a good method of inquiry for a group because this group already exists and they have this huge pool of data. (P3)

> I guess just like one thing with the internet is it does like bring together large groups of people instantaneously pretty much so you knows it's good that there's always at least the availability at least to start like a massive movement almost at the drop of a hat where you can rally people around an idea. (P4)

These excerpts illustrate how participants viewed 23andMe as a resource for bringing people together to learn new information or to work towards changing the status quo.

8.6.2 Potential negative consequences

Alongside these envisioned positive outcomes, participants also discussed a range of privacy and ethics concerns associated with genetic information being aggregated by companies such as 23andMe and available online. These ranged from questions of data ownership and discrimination by employers or insurance companies, to more extreme visions of dystopian futures where people might be disempowered or separated into cast systems based on genetics. Interestingly, all participants also agreed that the potential benefits of genetic testing outweighed the possible negative consequences. Despite their privacy concerns, for instance, all participants were not too worried about a breach of security to the 23andMe site, which was noted in the 23andMe terms of use. Participants likened this possibility to someone stealing their credit card information (*e.g.*, "*anything could be compromised, this is no different*", P3; "*anything could get hacked, if I were to worry I'd keep my money in my mattress*", P5).

8.6.3 New ways of seeing

Finally, participants also reflected on future genetic testing technologies as not necessarily a means to a scientific end (*i.e.*, diagnosing a disease), but also as a new way of seeing or understanding the world. For instance, when asked to envision the implications of rapidly sequencing any genetic material, P4 discussed the value of *seeing* or knowing things more intimately:

> I'm not interested in finding out any 1 specific thing or looking for any 1 specific thing but like using it to observe the world in a different way that when I see things that are interesting, I can observe them even more like a camera like a microscope like a telescope. It's not because you're tying to find something out its the act of knowing like you know something more intimately because you've seen a different side of it. (P4)

Here, P4 reflects on widespread genetic testing as an opportunity to observe living and organic materials differently. To varying degrees, other participants expressed similar ideas, noting that tools for rapid genetic sequencing might help identify surrounding organisms or learn more about the world ("*it would be easier to figure out what things were made of*", P4; "*it might be really neat for findings things*", P1).

To summarize, this section highlighted participants' perspectives on the bigger implications of genetic testing, which ranged from positive consequences for healthcare and bringing people together, to questions about ethics and privacy, as well as new ways to see the world differently.

8.7 Biocitizen publics

Thus far, I presented a study of 23andMe users, including our study participants' and forum contributors' motivations, practices, challenges and reflections on the broader implications of genetic testing. Our findings are, in many ways, aligned with Rose et al.'s (2005) analysis of biological citizenship, particularly by showing how widely accessible genetic data contributes to the blurring of citizenship as a purely national concept grounded in geographic boundaries. Indeed, learning about ancestry was a key motivation for joining 23andMe, and this information resulted in feelings of 'connectedness' to other community members. Most directly, these trans-national connections were made evident through 23andMe's relative finder, which revealed genetic kinship between members all across the world; as well as forum features, whereby users interact with others who are, as one forum member put it, 'genetically similar'. More broadly, the service revealed trends in evolution and patterns in human migrations. In the words of one participant, these visualizations showed 'fluidity' rather than 'stability' between ethnic groups.

With ideas about biological citizenship thus rooted in notions of global inter-connectedness, users of 23andMe coalesce around scientific findings not as passive consumers of data but as active, trans-national participants interpreting, contesting, and/or validating their results. New practices, centered around contextualizing and making sense of genetic data are giving rise to sub-communities of users, not unlike the other citizen science publics I discussed in earlier chapters. Similar to publics arising out of shared concerns (*e.g.*, local air quality), 23andMe publics are predicated on pressing questions about personal identity, personal health, or family history. Also, like the traditional citizen science efforts to gather local and professional knowledge, 23andMe users share and reflect on personal experiences, lifestyle choices, environmental factors, and cultural beliefs along with their genetic data. These heterogeneous information sources are aggregated across the 23andMe platform, whereby users draw on the site's research and social tools to create hybrid assemblies of personal narrative, pluralistic discourse, and academic research.

Finally, when these assemblies of hybrid knowledge reveal discrepancies between genetic test results and what participants know about themselves and their world, users collectively contest the underlying data. The emerging dialogues critique the biases, methodology, and scope of professional research: from pointing out unfair funding influences, to speculating about the importance of environmental factors that may have been overlooked by studies, or pointing out limitations in participant pools. With this framing of 23andMe users as active science communities, there are many opportunities for HCI to support and sustain the resulting biocitizen publics. Not unlike HCI's involvement with other citizen science groups, future design trajectories might include: platforms for aggregating different types of knowledge; tools for contesting and legitimizing scientific research; and enabling agency within and across genetics communities. I continue by discussing these below.

8.8.1 Platforms for aggregating different types of knowledge

Our findings suggest that genetic test results were rarely, if ever, considered in isolation. Instead, 23andMe data—from one's risk of heart disease or ability to taste bitter foods, to percentage of Balkan heritage—was contextualized within personal experiences, family narratives, lifestyle changes, and cultural/historic information. While these links proved to be essential to users' understanding of their genetic results, much of this contextualization occurred outside of the 23andMe site, whether through external search tools or by drawing upon personal knowledge. HCI research can contribute to making sense of these diverse information channels through new data visualization techniques and sharing mechanisms.

One opportunity lies in treating genes as "informational pivots" that serve to aggregate information about environments, lifestyles, and backgrounds across users. For example, future HCI systems could use graph visualizations: genes can be presented as nodes with which users might associate (share) personal experiences, family histories, or cultural and historic knowledge. In addition, HCI may also explore different approaches for capturing personal narratives and experiences that are often linked with genetic test results by 23andMe users. While the 23andMe service currently only supports text-based input across forums, future systems can enable rich multi-modal metadata to be attributed to specific genes. For instance, users may want to share visual (photos, videos) or audio experiences of living with certain genes.

On a higher level, considering personal genetics as a first-class organizing principle throughout online services has the potential to change the way we organize, seek, and share information. With connectedness being a key value for 23andMe communities, this approach could more intuitively reveal links between biology, people, and environments. Interfaces with genes as pivots could enable fluid navigation between scientific data and other factors such as local history, morals, and personal relationships, resulting in more coherent forms of biological citizenship (Lee, 2003). Building on HCI's understanding of 'politics of scale', such platforms can enable people to become connected not only through their actions (Dourish, 2010) but also through their genes.

8.8.2 Tools for contesting and legitimizing scientific research

Aggregating personal experiences, cultural knowledge, and external datasets along with genetic data led participants to question and critique the validity of the underlying research. Indeed, genetic test results were almost never accepted as matters of fact. From the fundamental role genes play in personal health and identity, to study size and data quality, and financial or political biases in academic research, participants actively problematized, questioned, or validated 23andMe data and personal knowledge. Here, new HCI is presented with opportunities to support public discourse around scientific findings, and provide mechanisms by which people can collectively critique scientific research.

Most directly, future systems can serve to fluidly support the practices of legitimizing or contesting scientific methods and findings. On one hand, sharing mechanisms could be tied directly to representations of the underlying genetic studies to enable people to discuss, make sense of, and evaluate the underlying science. For example, services such future personal genetic systems could enable users to comment on and rate study size, data quality, biases, claims, and other aspects of the research that is drawn upon to present the genetic results. On the other hand, systems could more deeply engage people with the scientific method, enabling members of the general public to effectively formulate hypotheses, explore the underlying data, and validate the results.

Of course, tools for contesting professional research raise questions about the scientific literacy of participants. While earlier research has commented on the limitations of more traditional tools to codify and transfer scientific knowledge (Bos, 2007), services such as 23andMe present new opportunities for disseminating information to people with varying degrees of expertise. 23andMe, for instance, supports scientific literacy by communicating information in a variety of ways, from short layman summaries or star confidence ratings, to extensive excerpts from academic publications. Citizen science systems in other domains (*e.g.*, environmental monitoring) could adopt similar or new visual techniques to make scientific data more transparent and legible. For instance, systems focused on factors such as air quality or phenology could more explicitly represent aspects of the contributing research, such as sample size, duration of studies, reproducibility, and how the work was funded.

8.8.3 Supporting agency within and across communities

Finally, it is important to note that as 23andMe users made sense of and evaluated their results, they inevitably commented on the broader implications of genetic testing. From the limitations of professional research approaches, to potential improvements to public healthcare, bringing large groups of people together, concerns about ethics and privacy, or the possibilities of seeing the world in new ways, 23andMe users engaged with the larger issues around genetics. Here, HCI has the opportunity to support new forms of activism around shared issues within and across communities.

With critique of genetic research being a prevalent practice throughout 23andMe, HCI can enable groups to more directly impact professional science work. For example, new tools might allow 23andMe users to create and contribute to advocacy initiatives around genetics research that is relevant to their lives. This could take on the forms of public awareness campaigns to nudge science agendas, tools to encourage more people to participate in science studies, or platforms for raising money to fund new research projects more directly.

In parallel, HCI can leverage design to more deeply engage members of the general public in broader discourse around bioethics, healthcare, and public participation in science. For instance, work in tangible interaction can overtly reveal recent trends in biotechnology research by incorporating genetic information and organic materials into tangible artifacts. New interactive experiences might highlight different biological aspects of the living world. Enabling people to see more intimate information within their bodies and the living systems around them (i.e., new ways of seeing) might bring about new forms of reflection and action within and across groups. More broadly, new research can focus on democratizing science by interfacing genetic research with related policy-level or healthcare debates and decisions.

8.9 Summary

In this chapter, I have presented the motivations, challenges, and practices of 23andMe users. My research methods included analysis and coding of 150 23andMe forum threads, followed by a qualitative study of six individuals who joined and used the service over the course of 3 months. Findings from this work reveal how participants come to understand and make sense of their genetic information, how this information is contextualized and acted upon, and how it serves to further scientific knowledge production.

In particular, I highlighted how participants are similar to other, more-widely studied citizen science publics in that they often turn to genetic research to resolve particular concerns, gather personal and professional information, and act on the collectively constructed knowledge. However, unlike more traditional citizen science groups, members of 23andMe are motivated by finding out deeply personal and intimate information such as where they came from and where they might be headed based on their genes. As a result, their scientific practices—how they contextualize their genetic results, critique and evaluate the underlying research, and reflect on the broader implications of genetic testing—are often deeply personal, and at times ethically charged.

Our design implications suggest applying HCI to new platforms for aggregating diverse information; designing tools for contesting and legitimizing scientific research; and supporting agency within and across the communities. As genetic testing continues to become more accessible, emerging publics will grapple with increasingly complex scientific information to make sense of their environments and themselves. It is critical for HCI to engage with this space to help define how genetic data can be made more valuable in negotiating the meaning of identity, family, and scientific participation.

9 Conclusion and future work

This dissertation aimed to expand the scope of HCI citizen science research towards a more holistic understanding of public participation in science. I framed this space in terms of citizen science publics: the processes by which groups of people coalesce around scientific issues, gather information, create artifacts, and work towards changing the status quo. Framed in this way, I discussed the sociotechnical practices of new and existing citizen science initiatives as publics participating in science outside of professional settings. In particular, I highlighted the importance of personal intuitions and local narratives as part of the data collection phase; collaborations between hobbyists, practitioners, and scientists; the resulting virtual and physical assemblies of hybrid knowledge; and finally, the broader impacts of scientific endeavors as they transform public policy, professional science research, and cultural practices. With this framing as a backdrop, I identified opportunities where HCI can radically innovate the flow of information between stakeholders, materials, and environments.

9.1 Summary of contributions

I began with an overview of how citizen science efforts are catalyzed by matters of concern, giving rise to communities that gather lay and expert knowledge, and how heterogeneous assemblies of materials, information, and values created by these groups serve to initiate broader changes. My work then applied HCI methods—from in-depth field studies, to the development and deployment of functional prototype systems—across these areas.

I first focused on new HCI platforms for expressing matters of concern. In Chapter 3, I presented the design of place-based sensors that enabled urban communities to articulate and come together around environmental issues. This work served to expand the role of sensors from being passive instruments of data collection and towards active platforms that demarcate space with stakeholder concerns. Then, in Chapter 4, I explored spectacle computing and tangible media as an approach for vibrantly and overtly broadcasting ideas into the public sphere. Using WallBots, interactive, wall-crawling robots, as a research probe in a study of street artists and activists, I detailed existing practices behind public expression. With DIY being a key value for these practices, I designed a low-cost kit that enables communities to assemble their own air quality sensors and create spectacles around vibrant balloon visualizations of air quality. This work highlighted the importance of stakeholder involvement in the making of sensing tools, as well as the power of spectacle for expressing concerns.

Upon thus examining how matters of concern might be expressed through interactive systems, I detailed a study of knowledge-gathering practices amongst individuals who use organic systems as sensors (Chapter 5). I highlighted new ways of seeing by describing how practitioners skillfully "read" bioindicators such as bees, plants, fish, and reptile to infer information about the environment. Building on these findings in Chapter 6, I presented the design and deployment of hybrid systems that incorporate organic, analog, and digital materials into sensing systems. These heterogeneous systems served to materialize local knowledge and community concerns by visualizing particulate pollution with paper-based collection and microscope magnification, and microbial activity in soil with bio-electronic sensing.

Finally, I studied the mechanisms by which citizen science publics catalyze broader changes in the status quo. My work with DIYbio practitioners and platforms and 23andMe users (Chapters 7 and 8) examined how stakeholder communities are transforming science practice from the bottom up. My fieldwork, hands-on experience with tools such as OpenPCR, and prototyping of design artifacts revealed the processes by which these groups gather diverse information and create heterogenous assemblies of online, physical, and biological systems. These hybrid tools and practices are enabling public engagement with scientific information embedded in organic materials, including the human body, and broadly impacting the mechanisms by which professional science operates.

In summary, my work presented deep insights into how HCI can support science practice outside of professional settings by engaging with citizen science publics. The particular touchpoints for HCI include 1) expressing matters of concern, 2) gathering knowledge, 3) making hybrid assemblies, and 4) empowering groups to enact change. While the first two areas have generated a large body of work within HCI—with, for instance, the development of expressive technologies and participatory sensing systems, the latter two pave the way for new and largely unchartered research trajectories.

9.2 Future work

9.2.1 Hybrid materials and assemblies

Hybridity has been a key area of inquiry throughout my dissertation. Drawing on Latour's discussion of *things* as heterogenous and active gatherings (2005), and design approaches embracing seamfulness (*e.g.*, Chalmers et al., 2004), I have studied and designed systems that bring together different materials, people, and values. I examined this area both by incorporating a range of new materials into the design of artifacts, and by considering how such hybrid assemblies influence and are influenced by human practices more systemically. Future HCI research can continue along this trajectory by innovating tools and methods of making.

Integrating analog, organic, and digital materials

New technologies are enabling practitioners within and outside of academia to create and experiment with hybrid systems. In my dissertation, I discussed how non-digital, DIY materials such as balloons and paper could productively contribute to the design of sensing systems. I also presented a range of possibilities for novel bio-electronic configurations. As visionary hybrid technologies such as the Lilypad (Buechley et al., 2008), which merges textiles with electronics, continue to advance our field, it is important to ask, what are the implications for HCI when organic materials are integrated into interactive systems? To be clear, this is not a speculation on a far-away science fiction future: a number of low-cost kits that use electronics to manipulate organic materials such as DNA or bacteria are already available for purchase, while many other combinations are being designed and assembled in DIYbio and professional labs around the world. What then are the challenges, and more importantly, the outcomes of these emerging hybrids, which leverage living organisms as inputs and outputs, and how can HCI contribute to their development?

Materializing issues and concerns

Incorporating novel materials into interactive systems offers range of possibilities for giving physical form to issues and concerns. In particular, the convergence of biology and computation presents a rich design space for exploring bioethics. For instance, the two bio-electronic prototypes I developed—the soil sensing system (Chapter 6) and bioluminescent algae device (Chapter 7)—intentionally and provocatively juxtapose organic processes with digital representations. These design decisions, whether appropriate or not, aim to foreground tensions between the organic and digital by quantifying natural qualities—soil microbial activity as a bar graph and algae color as a precise number. Future work can focus on bio-electronic assemblies that overtly reveal and even exaggerate similar issues, from the ethics of manipulating living organisms (for instance, by pressing a button to stimulate algae) to the philosophical questions of reducing living entities to simple inputs and outputs that are treated as parallel to digital sensors and actuators. Such hybrid artifacts might serve as boundary objects, materializing ethical concerns to engage biologists, hobbyists and members of the general public in productive discourse around the future of biotechnology.

9.2.2 Catalyzing broader impact

As I discussed throughout my dissertation, citizen science initiatives often catalyze broader changes in healthcare, policy, mass media production, and public engagement with science. While my work has predominantly focused on how bottom-up movements transform science practice in and outside of professional laboratories, other areas of impact remain to be explored. At the very least, HCI approaches can be applied to integrate grassroots initiatives with top-down decision processes, by, for instance, sharing citizen-collected data with city officials and policy makers. In parallel, HCI systems can support broader scientific literacy and participation in science on a larger scale.

Scientific literacy

My work illustrated how knowledge is often co-constructed between scientists and non-professionals. From long-running environmental initiatives whereby local data is analyzed by researchers, to the more recent open source biology movements that import professional knowledge into publically accessible practices, or emerging communities that interpret, contest, and legitimize genetic findings, this co-production of knowledge serves to broaden scientific literacy. Knowledge transfer between practitioners with varying degrees of expertise presents many opportunities for HCI. On one hand, new information-sharing tools can go beyond text-based tutorials to capture the unique hands-on nature of scientific exploration—from monitoring environmental factors to wetlab biology work. For example, new interactive technologies can be created to better visualize the steps of different biology protocols: pipetting, vortexing, or centrifuging could be presented *in-situ*, on multi-touch tables, phones, or tablets. Moreover, as technologies such as OpenPCR and PearlBiotech enable new ways of seeing foods, plants, insects, and other aspects of local ecologies, much work remains to be done in making these tools more user-friendly and accessible. My own research has shown, for instance, that the interactions afforded by emerging DIYbio technologies are still very limited. Here, HCI can radically innovate the way these tools are used, making the surrounding biology protocols easier to follow and the resulting data more intuitive to understand and share.

More broadly, scaffolding tools can serve to connect people within and across communities and support mentorship and learning. Future interactive systems might connect individuals with different skillsets, or enable expert practitioners to more fluidly record, annotate, and share their work. Social media or crowdsourcing platforms can also serve to troubleshoot problems in scientific procedures, optimize protocols, or make certain steps easier or safer. New knowledge sharing tools might also serve as sources of inspiration and creativity. For example, devices, not unlike the design exercises I developed in Chapter 7, might be situated in workspaces to display SMS questions, answers, or ideas for future projects. These tools, along with new sharing mechanisms, might foster productive collaborations between scientists, designers, and hobby practitioners.

DIY and scale

Along with supporting scientific literacy, HCI can pave the way for larger-scale scientific participation. My dissertation, has specifically explored hands-on-making and DIY platforms for public engagement with science. HCI can continue contributing to this area through the development of new DIY tools and kits that scale to large groups of people. Similar to the balloon air quality sensing kit, for instance, other easy-to-assemble sensors can enable groups to create their own sensors that measure water, air, soil quality, or track the well-being of local organisms. Incorporating low-tech materials such as paper, or existing living systems such as bees, plants, or reptiles as bio-indicators, might further reduce the costs of large-scale data collection. Moreover, low-tech and no-tech materials might enable more organic scaling of such systems across different user groups.

New DIY approaches can also enable stakeholders to modify and customize science tools to fit their needs, shifting away from one-size-fits-all systems as I suggested in Chapter 3. In the process of developing such tools, HCI will be faced with balancing trade-offs between cost, precision, and scale. New algorithms might be applied to reduce noise or correct error in crowd-collected datasets. Other approaches may focus on leveraging existing technologies (such as cameras or microphones in mobile phones) to support accurate calibration procedures.

Transparency

Finally, HCI techniques can transform traditional scientific tools into public engagement systems, similar to how I re-envisioned sensing as an approach for broadcasting information into the public sphere. On one hand, new interactions and data visualizations can shift scientific machines (microscopes, PCR machines, etc.) from collecting data and towards also sharing information with larger audiences. Outwardly-facing scientific instruments can embrace transparency, both within professional science practice and between the various stakeholders that influence science agendas. At the very least, foregrounding interactions with tools in DIY and professional settings can demystify lab practices and involve a range of stakeholders in scientific discourse. Here, challenges for HCI range from the practical considerations for fluidly attributing metadata (*e.g.*, GPS, time or care instructions) to the information collected by such tools; to the mechanisms for sharing this information with stakeholders such as novice practitioners, policy makers, or the wider public; and the higher-level implications of mediating dialogues across these groups. This presents opportunities to rethink hardware platforms (*e.g.*, microscopes) as instruments of public debate and in turn re-envision modes of science making across DIY and professional labs.

To summarize, I have outlined several future trajectories for HCI research to support bottom-up participation in science. I suggested that new materials and methods of making, with a particular focus on bio-electronic hybrids, present rich opportunities to assemble data and concerns into physical forms. These hybrid assemblies and a deeper involvement with DIY cultures can, in turn, pave the way for larger-scale scientific literacy and participation.

9.3 Final remarks

I began my dissertation by asking how HCI can support science practice outside of professional settings. This question is of increasing importance as advancements in sharing platforms, affordable technologies, and methods of making continue to blur the distinction between professional and amateur science. With scientific concepts so often pervading mass media, political discourse, and everyday products, the notion of a passive "non-expert" science consumer is becoming obsolete. Indeed, even some of our most routine decisions are predicated on an understanding of science—from choosing between organic, endangered, invasive, or genetically modified foods, to relying on patented pharmaceuticals and medical procedures, or selecting sources of energy and transportation that have impact on the environment. By making these choices, we all, to some degree, play an active role in the complex arena between professional science and the public policies, products, and practices that legitimize or contest it.

Citizen science initiatives, as I have shown, are collective efforts to construct knowledge and address issues. These issues often touch upon the greatest challenges of our lives: environmental pollution, food production, healthcare, and climate change, to name a few. Amidst these concerns, citizen science publics form deep entanglements between people, materials, and values. My own work in this space has operated at the seams, much like citizen science does, to uncover the mechanisms by which publics come into being, and suggest corresponding HCI strategies for supporting these. I hope future research continues to empower active participation in science, within and outside of professional settings.

10 References

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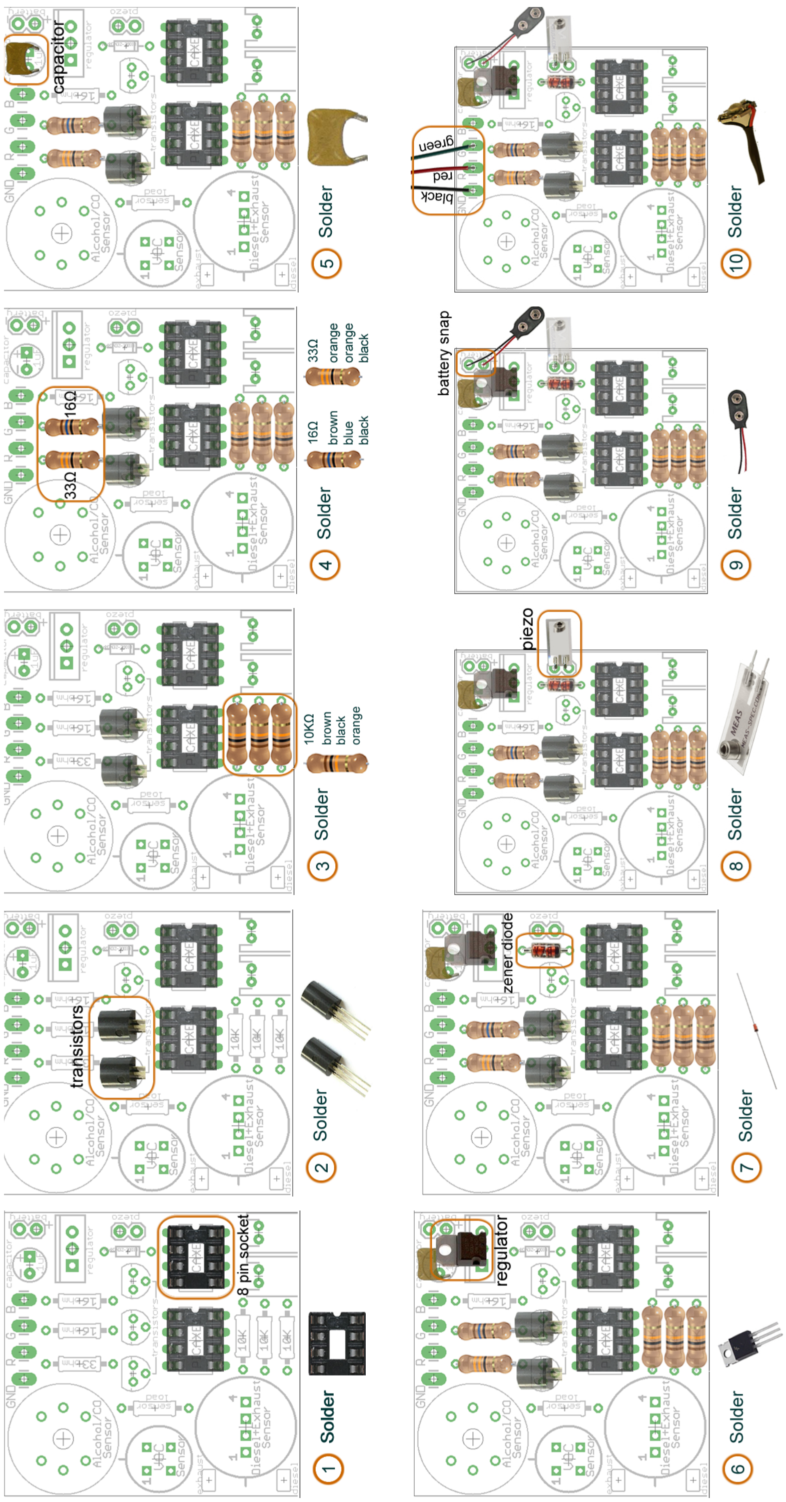
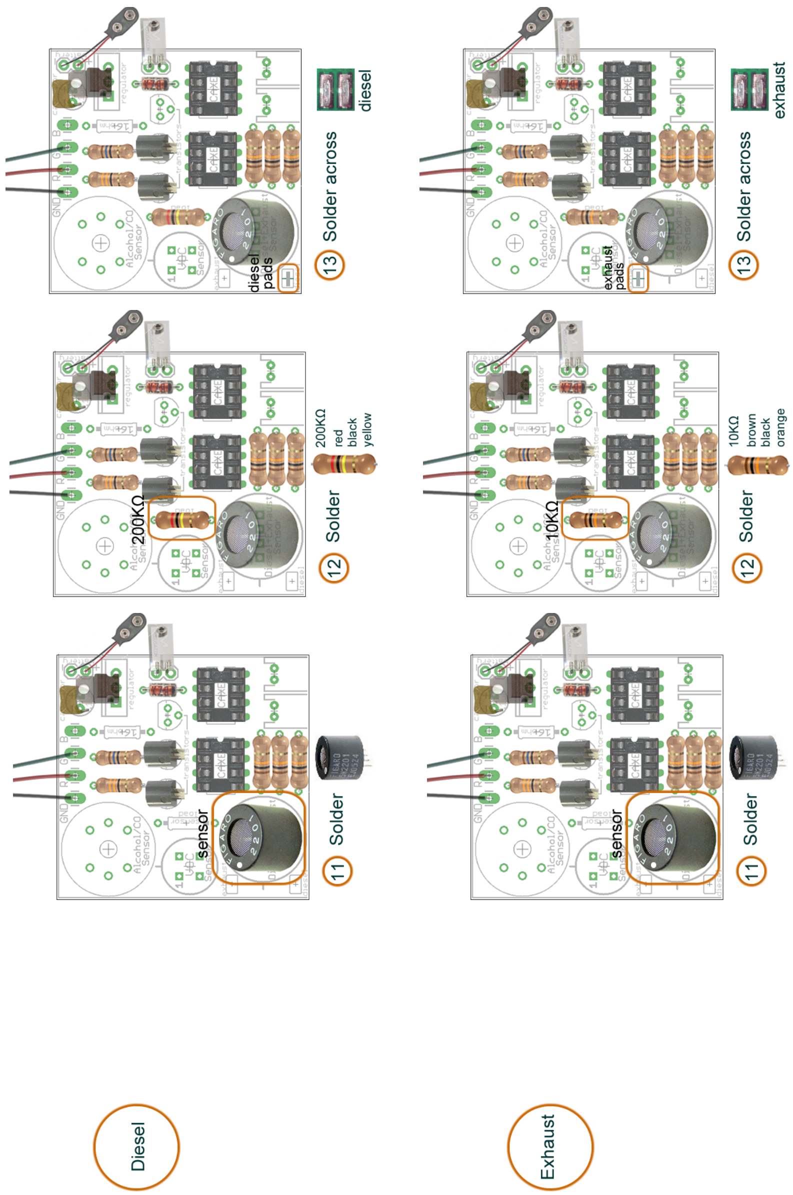
Appendix 1: Balloon board assembly instructions


1 Solder
8 pin socket
2 Solder
transistors
3 Solder
10KΩ brown black orange
4 Solder
33Ω
16Ω
16Ω brown blue black
33Ω orange orange black
5 Solder
capacitor
6 Solder
regulator
7 Solder
zener diode
8 Solder
piezo
9 Solder
battery snap
10 Solder
black
red
green


Diesel
11 Solder
sensor
12 Solder
200KΩ
200KΩ red black yellow
13 Solder across
diesel pads
diesel
Exhaust
11 Solder
sensor
12 Solder
10KΩ
10KΩ brown black orange
13 Solder across
exhaust pads
exhaust