Community Engagements with Living Sensing Systems

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ABSTRACT

We present the design and deployment of a bio-electronic sensing system. This system visualizes bacterial activity inside *Winogradsky columns*, which incubate soil samples to culture the naturally occurring microorganisms as they process metals and nutrients in the soil. Our month-long deployments with two urban communities offer insights into individual and collective appropriations of living sensing systems. These findings reveal future design trajectories that build on emergent themes in Human-Computer Interaction (HCI), including: new perspectives on materiality, which arise from integrating organic materials with the digital; a reframing of time, as systems shift from providing instant feedback to supporting prolonged engagement; and an emphasis on collective modes of participation beyond individual behavior change.

Author Keywords

Biosensing, slow technology, citizen science, DIY

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Human Factors; Design.

INTRODUCTION

Digital sensors enable us to collect and analyze environmental data, often with remarkable degrees of precision. From personal devices to public sensors, HCI research has empowered users to monitor factors such as air pollution, water flow in creeks and metal content in soil [7, 20, 32]. Compelling visualizations of this citizen-collected data (*e.g.*, graphs, maps) provide powerful tools for analysis. However, as non-experts and scientists alike continue to rely on digital technologies to measure and quantify the world around us, we are left to ask, to what extent does digital sensing *limit* our understanding of, reflection on and attunement to the environment?

An emerging body of HCI work emphasizes expanding the scope of environmental sensing beyond the development of digital tools. Political participation, community dialogues and co-production of knowledge between scientists and non-experts are just a few of the critical dimensions for participatory sensing research that have been highlighted [9, 10, 29]. Recent work also proposed expanding HCI's vision of sensing to include organic systems along with digital devices. Drawing from a study of individuals who routinely rely on living organisms such as bees, plants, reptiles and fish to infer information about the environment, Kuznetsov, *et. al* show that biomarkers and bio-indicators lend themselves to '*new ways of seeing*' [25]. That is, living systems enable us to engage with and reflect on the world in ways that digital devices often fall short of supporting.

Alongside this work, a growing number of projects have begun to integrate organic and living materials as inputs and outputs into '*bio-electronic hybrids*' [24]. Examples include *OpenPCR*, an open source tool for performing Polymerase Chain Reaction outside of professional laboratories; *I/O Plant* [22], which enables designers to manipulate plants through sensors and actuators; *Botanicus Interacticus*, a system that supports expressive interactions with plants [36]; and 'virus energy generators' [21]. 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 [15]; the uncertainty of living processes might serve as a point of reflection on

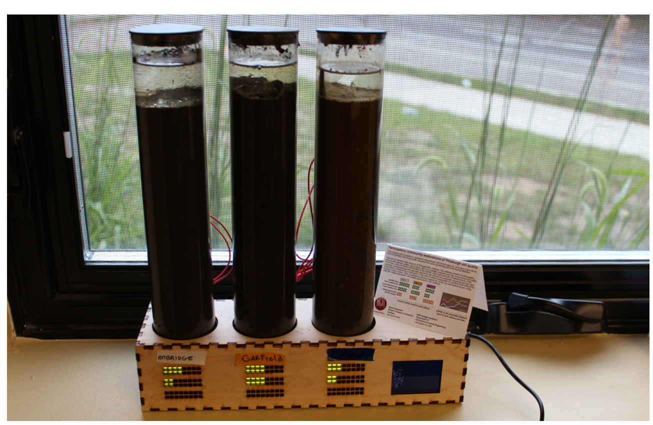

Figure 1. Bio-electronic soil sensing device deployed at an environmental outreach community center.

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ambiguity in design [13, 38]; the nuances of sustaining and supporting life might result in new forms of community engagement and participation [1, 10]; the de-emphasis on technology itself can be treated as parallel to sustainability work considering 'low tech' and 'no tech' solutions [2, 5].

In this paper, we begin to explore these ideas through the design, development and deployment of a bio-electronic soil sensing system (Fig. 1) that monitors the progress of *Winogradsky columns*. 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 [37]. Our system visualizes bacterial activity in the columns by measuring soil conductivity and the voltage potential (energy) generated. Workshops and long-term deployments with two urban communities offer insights into individual and collective appropriations of bio-electronic sensing. Our design implications identify several opportunities for future work: (1) integrating digital and organic materials; (2) prolonged engagement with systems; (3) new modes of participation; and (4) ethical considerations.

CITIZEN SCIENCE AND PARTICIPATORY SENSING

In HCI and elsewhere, citizen science is often defined as 'non-experts' collecting, sharing and acting on environmental data. Traditionally, much of HCI research has focused on participatory sensing: methods and systems (mobile phones, handheld devices) for data collection and tools for sharing data within and across communities [29]. For instance, interventions such as *inAir* enable friends to view air pollution levels in each other's homes [20], while *Suelo* focuses on improving the accuracy of a distributed soil-sensing network [32].

As Coburn shows in a range of case studies, citizen collected environmental data often goes beyond digital measurements to include experiences, intuitions and observations of local residents [9]. These narratives are shared not only across local groups as is sometimes scoped by HCI research [*e.g.,* 40], but also between scientists and non-experts, ultimately leading to co-production of knowledge between experts and amateurs. Furthermore, this information is often actionable beyond individual behavior change, but also as a catalyst for broader processes in environmental policy, mass media, *etc*.

In line with Coburn's research, recent HCI work has explored more systemic approaches to participatory sensing. For instance, the *Common Sense* project invited participants to annotate digital measurements with personal narratives [40], while participatory design work involved communities in the development of sensing systems from the bottom up [*e.g.*, 10]. In parallel, tools have been developed to support scaffolding and sharing between scientists and non-experts, such as a digital augmentation of outdoor environments to facilitate learning [33], or mobile phone applications to encourage outdoor observations [35].

Complementary to these approaches, systems that integrate organic materials offer a new point of reflection on some of the critical themes within participatory sensing: *precision, time, materiality* and *participation*. We continue by discussing how these ideas are treated within and outside of HCI's citizen science research.

Precision

Throughout participatory sensing, emphasis is placed on accuracy and precision. Calibrations, error rate, and comparisons with scientific instruments are common evaluation metrics. In addition, visualizations often facilitate specific judgments about the world: 'traffic light' metaphors convey that air quality is either good or bad [23], graphs and numeric displays draw attention to high/low values [29, 40]. As an alternative, HCI has been exploring design strategies that embrace ambiguity [13]. Critiquing the dominant idea that systems should convey a single, authoritative interpretation, Sengers and Gaver suggest that multiple meanings can fruitfully co-exist between user, system and designer [38]. Designs that support this multiple meaning-making will likely embody the quality of pluralism, which "refers to design artifacts that resist any single, totalizing, or universal point of view" [1]. Living systems naturally lend themselves to multiple interpretations and pluralist qualities of interaction.

Time

Efficiency is often discussed alongside precision in participatory sensing. Hand-held devices quickly respond to changes in the environment [40]; data from sensors is uploaded to websites in real time [29]; and information is instantly shared across users and groups [20]. In parallel to the rhetoric of efficiency and performance, '*slow technology*' is a design agenda that promotes "reflective use" above functionality [15]. This work explores systems that create 'reflective environments' as they are *lived with*, rather than *used* to complete specific tasks [15, 28]. Bio-electronic sensing systems are aligned with the slow technology agenda in at least two ways. First, organic processes tend to be more complex and operate at different time scales than digital devices. Second, tacit understanding of living processes is acquired over longer periods of time.

Materiality

Environmental sensing systems tend to interface users directly with the physical world, either through tangible interaction with cell phones and hand-held monitors in the field, or through virtual representations (maps, graphs, etc.) of 'real-world' data (*e.g.*, soil pH). In this regard, all sensors and the materials being sensed necessitate a discussion of materiality—a discussion that tends to be lacking from most participatory sensing literature in HCI. Historically, separation of function and form is dominant in computer science: decoupling, modularity and abstraction are often associated with a "*digital-physical divide*" [4]. This 'divide' is explored by tangible interaction work, and most notably bridged by Ishii's vision of 'tangible bits' [19], among others. While digital sensing can rely exclusively on the transmission of virtual information in the form of electronic signals, biosensors typically involve living, organic, and molecular processes that materially embody the world being sensed.

Participation

In HCI, the deployment of environmental sensors often involves giving participants devices to use or 'try out,' and/or prompting them to interact with the data. More often than not, these types of deployments are treated as usability studies 'in the wild', establishing a '*scientific distance*' between participants and researchers [1]. Participatory design offers a parallel approach, which "avoids the scientific distance that cuts the bonds of humanity between researcher and subject, preempting a major resource for design (empathy, love, care)" [1]. Recent projects [*e.g.*, 10] effectively change the '*quality of participation*' [1] by collaborating with stakeholders to co-design environmental sensors. Bio-sensing systems offer a complimentary perspective. On one hand, the complexity of living systems and the knowledge required to understand them might bring about productive intersections between non-experts and scientists, similar to how the DIYbio (Do It Yourself Biology) community is immersed in a discourse between biologists and hobbyists [24]. Moreover, the experience of working with living materials—from sustaining life by ensuring specific conditions to feeding and 'caring' for the system—might support more nuanced and empathetic relationships between people who are traditionally deemed 'users' and 'researchers.'

To summarize, we have outlined four areas—precision, time, materiality and participation—as critical dimensions of participatory sensing. Drawing on interdisciplinary literature, we have argued that bio-electronic systems offer an alternative lens for exploring these themes.

DESIGNING A BIO-ELECTRONIC SYSTEM

We continue to expand on the above ideas by detailing the design of our own bio-electronic soil sensing 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 [39].

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 [25]. Prior soil sensing research focused on distributed sensor networks to support agriculture [3, 17, 31]. Complimentary to this work, we explore a visualization of Winogradsky columns to foster community engagement with soil.

Winogradsky columns

Designed by and named after Sergei Winogradsky, a scientist deemed "father of microbiology" [11], 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 [37]. 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 [27]. We chose to focus our design 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

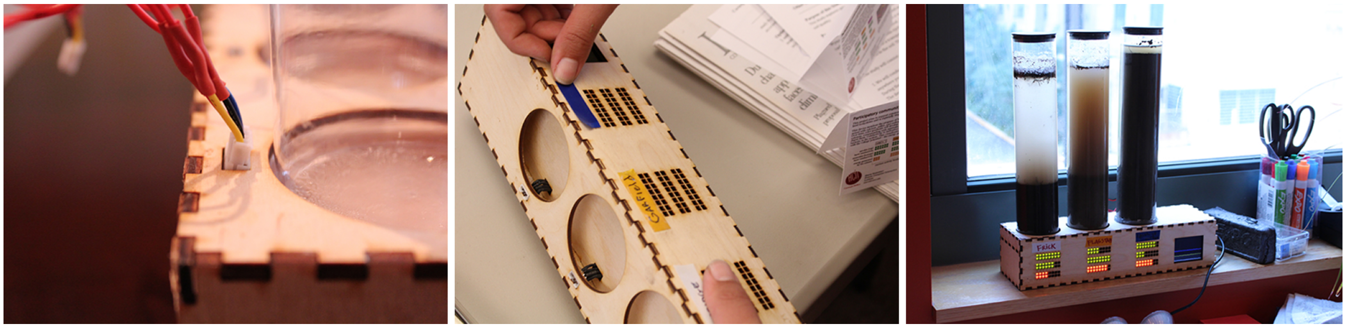

Figure 2. Designing a bio-electronic system: column plugged into casing; labeling the column slots; testing the system.

from a recently remediated dumping site for steel mills showed little activity (both visually and 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.,* 14], 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). The columns can be 'plugged' into or detached from the wooden casing (Fig. 2) 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.

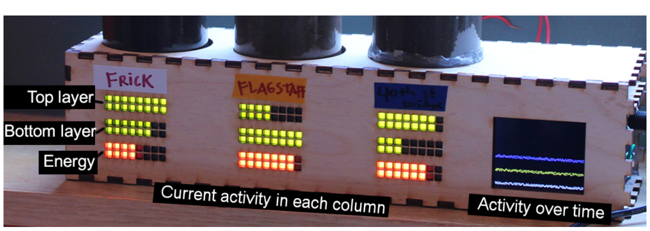

Figure 3. System visualization with components labeled.

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 (Figure 3). 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. 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.

COMMUNITY WORKSHOPS AND 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 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.

FINDINGS

We 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. 4). 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, as in [23]). 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 back 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.

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.

Figure 4. Community soil workshops: using a potassium test kit, mixing column contents, sensing system placed by cash register.

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 <u>it's definitely grown</u> 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):

> *"<u>There are things that in real life they just take longer to do</u>. 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 <u>especially in the timeframe of like gardening</u> 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:

"<u>I prefer the slow methodical side of technology to the instant gratification, sort of things</u>... 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. <u>I think it's really cool to be able to track things and follow things</u>... <u>it's more fun and engaging</u>."[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 <u>the overall health and what's going on in there, the activity</u>." [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.

DISCUSSION & IMPLICATIONS

Earlier in the paper, we discussed how themes such as precision, time, materiality and participation are treated within participatory sensing research and across other interdisciplinary design work. Our bio-electronic sensing system offers a new lens for exploring these ideas, both through our design process and our participants' reflections during the deployment. In this way, our approach is 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 [12]. In what follows, we more broadly reflect on our findings to open up opportunity areas for future citizen science research.

Seamfully interweaving organic and digital materials

Seamful computing celebrates points where diverse materials, as well as people, technologies, and contexts coalesce [8]. These intersections serve as generative areas where new knowledge and practices can emerge. Our sensing 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: the columns' slower timescale, light and temperature requirements, and unique physical form necessitated an immersive design process within our multi-disciplinary team. Likewise, participants' physical interaction with the soil—an organic and arguably more familiar material than digital sensors—led to community knowledge sharing through narratives.

These findings are aligned with prior work, which suggests expanding HCI's vision of sensing to include organic materials [25]. Future sensing systems can leverage 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 systems are, by definition, active and embedded in our physical surroundings. Recall 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, 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" [30]. When considering organic properties, we inevitably confront questions of form. In our design process, the strange yet familiar qualities of the Winogradsky column were highlighted by the aesthetic of the final system. With form being essential in design research, such as, for instance, in the design of Gaver, *et. al*'s *Prayer Companion* [14], it is critical to consider what new forms might emerge as organic and digital materials are combined into transmaterials, hybrids and composites. This suggest opportunities for work incorporating 'active' materials—bacteria, plants, animals—into sensing systems to explore how these might radically shift our understanding of what a 'sensor' looks and feels like, as well as what it means to 'read' it.

The integration of digital with the organic also raises 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.

Prolonged engagement with *systems*

Our findings suggest that soil tests for specific factors (pH, nitrogen, *etc.*) 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 [20]. 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 [16]; GPS navigation might disengage drivers from their surroundings [26], *etc*.

As an alternative to measuring specific soil compounds, our bio-electronic system served to focus participants' intuitions, deliberations and discussions '*around a topic*' [38]. Organic and digital components were fluidly drawn upon over time to infer the 'overall health' of their soil, or link the system with broader processes such local weather. These results highlight a more systemic approach to participatory sensing. Complimentary to sensing devices that report on specific factors (parts of a whole), new research can focus on revealing processes within and across *systems*. This view shifts our understanding of systems from being purely machine, to considering how living organisms (bacteria, birds, humans, *etc.*) interact with complex materials (air, water, soil, digital artifacts, *etc.*).

There are several opportunities for future research to leverage this perspective. First, design can shift from prescription to reflection [6]. Rather than facilitating specific judgments about the world (*e.g.,* I need to add fertilizer, *etc.*), new technologies can expand our focus by leveraging more holistic and less precise inputs and outputs.

For instance, a community garden system might show bee fight 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. By highlighting these broader relationships, systems will likely embody pluralist qualities of interaction and support multiple intuitions and interpretations [1, 38].

Second, design can move towards supporting prolonged engagements with systems. Given 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 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.

New modes of participation

Prolonged engagement with systems (both digital and organic) 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 system—the columns—using soil samples they dug up from their gardens. 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 [40]). 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 non-experts. During our deployment, for instance, participants reached out to people with scientific backgrounds to share the project, and envisioned its use as an environmental education tool. For HCI, this implies new opportunities for enabling 'open source science' [24], 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 [6] and towards richer collective experiences, provide opportunities for reducing the *scientific distance* [1] between researchers and participants.

Ethical considerations

While bio-electronic systems 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. 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.

CONCLUSION

We presented the design and deployment of a bio-electronic sensing system that monitors microbial activity in soil. Our design process and findings from two community deployments reveal an emerging intersection between biology and interaction design. This intersection presents a new platform for the design of future creativity systems. In particular, we have reflected on how incorporating organic materials into sensing systems provides new perspectives on materiality, time, and participation. We hope our work inspires broader discourse around bio-electronic hybrid systems both within and outside of the HCI community.

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