Integrating Living Organisms in Devices to Implement *Care-based Interactions*

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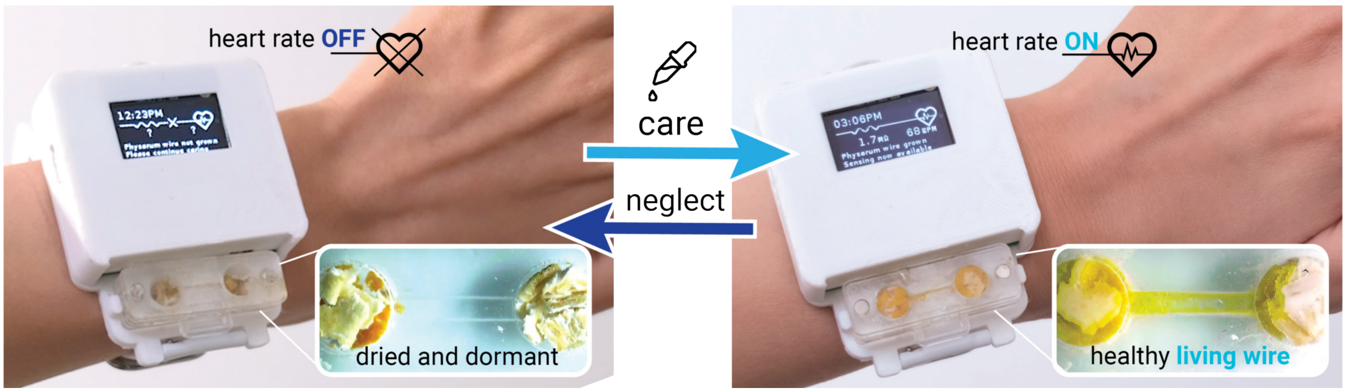

Figure 1: We explore how embedding a living organism, as a functional component of a device, changes the user-device relationship. In our concept, the user is responsible for providing an environment that the organism can thrive in by caring for the organism. We instantiated this concept as a slime mold integrated smartwatch. The slime mold grows to form an electrical wire that enables a heart rate sensor. The availability of the sensing depends on the slime mold's growth, which the user encourages through care. If the user does not care for the slime mold, it enters a dormant stage and is not conductive. The users can resuscitate it by resuming care.

ABSTRACT

Researchers have been exploring how incorporating care-based interactions can change the user's attitude & relationship towards an interactive device. This is typically achieved through *virtual care* where users care for digital entities. In this paper, we explore this concept further by investigating how *physical care* for a living organism, embedded as a functional component of an interactive device, also changes user-device relationships. Living organisms differ as they require an environment conducive to life, which in our concept, the user is responsible for providing by caring for the organism (e.g., feeding it). We instantiated our concept by engineering a smartwatch that includes a slime mold that physically conducts power to a heart rate sensor inside the device, acting as a living wire. In this smartwatch, the availability of heart-rate sensing depends on the health of the slime mold—with the user's care, the slime mold becomes conductive and enables the sensor; conversely, without care, the slime mold dries and disables the sensor (resuming care resuscitates the slime mold). To explore how our living device was perceived by users, we conducted a study where participants wore our slime mold-integrated smartwatch for 9-14 days. We found that participants felt a sense of *responsibility*, developed a *reciprocal relationship*, and experienced the organism's growth as a *source of affect*. Finally, to allow engineers and designers to expand on our work, we abstract our findings into a set of technical and design recommendations when engineering an interactive device that incorporates this type of care-based relationship.

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CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction devices.

KEYWORDS

Living organism, caring interaction design, slime mold, symbiosis

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1 INTRODUCTION

Interactive devices are designed to be easy-to-use, function fast, and act almost invisibly. These are key principles in Weiser's ubiquitous computing [70], which has driven decades of computing research and products. This vision enabled seamless interactions by designing for "invisible" devices. While this is desirable and useful in many ways, this invisibility is not without shortcomings. A striking one is that it has the unfortunate side-effect of conditioning users to see devices as distant entities or, even, conditions users to not engage with the environmental implications of consumer devices [9, 34, 42, 43]. As new devices are released, millions of outdated devices are thrown out in piles of e-waste—"a record 53.6 million metric tonnes of electronic waste in 2019, up 21% in just five years" [25].

Many researchers, thinkers, and policy makers argue for a different relationship with our devices [6, 8, 10, 26, 36]. In the HCI community, many have been exploring how to create alternative, more *caring relationships & attitudes* in the hope that by changing the relationship, users might connect more responsibly with their devices and thus extend their devices' lifetimes [11, 39, 40]. Some powerful examples include, incorporating *care* or *maintenance* as part of the interaction [40]; embedding a user's own personal histories with a device to promote keeping devices for longer periods [24, 55]; designing interactions to be *slow* and experienced over a long time [15, 56]; using *animated* materials to inspire a sense of aliveness [1, 7, 18, 20]; or integrating personalities in users' devices to promote kinship with the device by *anthropomorphizing* the devices [14, 16]. These approaches are similar in how they are attempting to make devices "appear more alive".

Simulating liveliness, in many cases, still falls short. A key historical example of this interface design is the *Tamagotchi*, a popular interactive device from the 90s in which users took care of a virtual pet by feeding it and watching it grow [44]. While this interactive device allowed users to develop caring attitudes, after the novelty of the experience wore off, most Tamagotchis were discarded [12, 58]. Ultimately, these virtual care-based devices offer potential (and have many advantages that stem from their virtuality) but, just like the Tamagotchi, these devices are constructed from inert materials, which signal to the user that the *care is virtual*, making it harder to feel empathy or responsibility [27, 49].

Instead, we propose & explore **how integrating a living organism in the functionality of an interactive device changes the relationship**. We achieve this by implementing a *physical* care-based interaction. Living organisms need an environment they can thrive in. This makes them notably different from virtual organisms or the inert materials that make up most interactive devices. In our concept, the user is responsible for providing this favorable environment by caring for the organism (through watering, feeding, etc.).

To explore this concept, we instantiated it in the form of a functional smartwatch, which includes a slime mold that powers a heart rate sensor inside the device (our slime mold acts as a living wire, as depicted in Figure 1). As such, the availability of heart rate sensing is dependent on the health of the slime mold. If the user cares for it, it grows to become conductive and enables the sensor. On the other hand, if the user does not care for the slime mold, it dries up and enters a dormant stage in which it is not conductive. The users can resuscitate it by, again, resuming care.

To explore how this living artifact introduces new relations between human, device, and slime mold we conducted a study where participants were asked to wear and care for the smartwatch and physarum device for 9-14 days. During this period, participants were asked to complete (1) a diary study where users reported their daily experiences wearing and caring for the device; and (2) interviews mid-way through and at the end of the study. From this study, we found participants felt a sense of *responsibility* towards their device, developed a *reciprocal relationship*, and experienced the organism's growth as a *source of affect*. Last, by drawing from our findings and process of engineering the care-based interactive device, we synthesized a set of recommendations for other researchers interested in building on our work.

Importantly, our goal is not to argue that technology must be hybridized with living organisms or that they offer technical improvements compared to inert materials (in fact, we acknowledge they have a range of disadvantages compared even to a simple copper trace) but, instead, we focused on exploring the implications of this type of physicalized care-based interaction and how future engineers and designers can center care in interactive devices.

2 RELATED WORK

Our work builds on top of interactive systems that explore alternative user-device relationships, such as explorations of slow technology or friction-based UIs. Our work is also inspired by existing care-based interactions that use virtual care to explore and foster a more personal and responsible connection with interactive devices. We also draw on previous approaches in collaborating with living organisms in the design of interactive devices. Finally, to give the reader the required background to replicate our technical implementation, we provide an overview of the slime mold organism used in our prototypes with an emphasis on the unique properties that make them viable as a functional material for interactive devices.

2.1 Alternative User-Device Relationships

Various HCI researchers have explored how we might foster alternative relationships and attitudes to our devices. Many achieved this by creating interactions that are distinctly different from the frictionless, invisible, fast, or productivity-oriented interactions that pervade most all devices.

Hallnäs et. al [31] presented *slow* technology as "technology aimed at reflection and moments of mental rest rather than efficiency in performance", which has since been explored in HCI to create moments of reflection with interactive devices or a slower temporality of interaction [15, 54]. Others have explored adding intentionally difficult to use interactions, making users reevaluate the way they normally engage with their devices. For instance, *Crank that Feed*, explored how forcing users to scroll through their twitter feed via a mechanical crank encouraged users to be more reflective about their interactions with the device they used for social media consumption [63]. Paulos and Pierce have proposed *Counterfunctional Things* as a design approach to intentionally create functional limitations for digital devices, such as by creating a camera that has to be smashed apart in order to access photographed images [60]. These approaches to reimagine our relationships to devices have similarly been explored across critical design [23], ludic design [28], speculative design [13], and adversarial design [11]. In our work, we are also interested in enabling reflective attitudes and relations to interactive devices and do so by redesigning a smartwatch to require *caring* for a living organism.

2.2 Caring Interaction Design

Many users might feel little responsibility for their devices as they can easily be replaced if broken or when a newer model comes out (which in many popular devices, like iPhones, is annually [73]). As e-waste becomes a growing issue globally, one way HCI researchers have focused on addressing this is by exploring how to foster caring relationships between user and device [10]. In *Proceed with Care*, Key et. al [39] explores how incorporating care ethics and *thingcare* in reimagining interactive devices might enable a more inclusive and responsible future of these technologies. Researchers have also explored care that goes into repair, maintenance, and creative reuse of device materials [35, 48, 67]. Others in HCI have explored how to enable caring interactions through the design of the interactive devices, creating interactions that encourage users to see devices as indeed, worthy of care. Oftentimes these designs involve forms of *virtual care* where users are meant to respond to qualities of livingness in digital entities.

2.2.1 Adding Virtual Care to Interactive Devices. Across HCI, much research has been devoted to developing highly useful applications to encourage users to feel invested and attached to their devices. These efforts are important in avoiding device obsolescence and, while these can also encompass a type of caring interaction, we are interested in interactions designed specifically to encourage users to feel responsible for their devices beyond their usefulness.

In interactive devices, this has primarily taken the form of virtual pets that require users to perform some sort of "care" to sustain them. The choice of a pet for these designs might appear inconsequential at first but it is effective and well-motivated in that humans display more emotional and responsible attitudes for pets than for inanimate objects [27, 46]. In this way, these devices alter the relationship by using the virtual pet to attribute characteristics generally seen only in a living animal or companion species to an interactive device [22]. The most striking historical example of an interactive device that included with a virtual pet is the *Tamagotchi*, which allowed users to grow different virtual pets by delivering various gamified forms of care [44, 58]. Outside of gaming and toys, these virtual pets or virtual companions have also been widely explored across HCI as useful for learning [33], companionship [45, 69], medical interventions [52], and more [21].

In virtual pet/companion experiences, users feel responsible for their interactive devices since caring for their virtual companion is intertwined with the device use. However, there is a limit to the attachment formed between user and virtual companion. Ultimately, users will understand that these companions are *virtual* and made of inert, inorganic materials that might feel easily disposable. Despite the excitement around caring for Tamagotchis at their peak, a few years later they became out of fashion and near obsolete, likely trashed or relegated to the back of closets [58]. As explained in *Disposable Love: The rise and fall of virtual pets*, "Tamagotchi is seen as a symbol of its times in which even the most intense connections are disposable" [12].

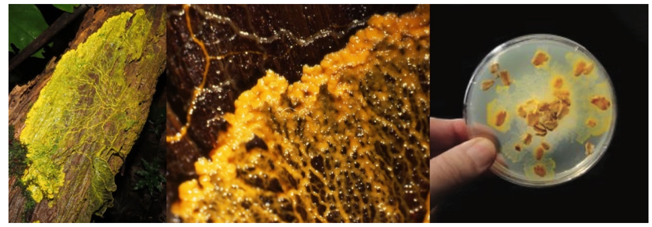

Figure 2: Images of Physarum polycephalum in the wild, growing naturally, and in a petri dish growing on oats. (Images courtesy of Rich Hoyer, Helen Ginger, Carolina Biological).

2.3 Living Organisms in Interactive Devices

Recently many researchers, designers, and artists have been interested in exploring what new interactive capabilities can be enabled through living materials [29, 38, 41, 59, 62, 68]. This has been primarily explored through Living Media Interfaces [51], which incorporate living organisms in interactive designs. For instance, Rafigh [32], Biogotchi [17], and recent work from Ofer et. al use living organisms as visual displays [57]. Other devices, such as Nukabot [16] or Project Florence [64], emphasize digitizing biological signals. By incorporating a living organism in their design, the care of and sustainability of the organism is inextricably involved too. However, in most cases the care of these organisms is not integrated in the interactions with these devices—the care for the living organism is not intertwined with the interactive functionality of the device itself. While a living organism is much less stable than inert materials (this is of course a major limitation using living materials), it also presents an opportunity for new relations based on care that might make users more considerate of the material properties of our devices. As such, we are interested in emphasizing the care work involved in integrating living organisms rather than relegating it to the background. In our example, we focus on care of a slime mold (Physarum polycephalum), chosen due to its unique biological capabilities.

2.3.1 Physarum Polycephalum. Finally, to give the reader the background to replicate our technical implementation, we provide an overview of the organism used in our prototype. *Physarum polycephalum* are single cell organisms known for their ability to grow towards food sources. While they can live as single cells, they often aggregate and propagate via growth and multinucleation, as depicted in Figure 2. This organism belongs to the *protist* family, distinct from fungi, plants, or animals. Scientists have studied them in a variety of contexts in the lab and in-the-wild. Due to their resilience and bio-safety level 1 (i.e., not known to cause disease in healthy adults and present minimal hazard), they are popularly used in educational science experiments in classrooms [13]. Important to note is that, unlike many other organisms, physarum polycephalum thrive well in non-sterile environments and feed from a variety of sources, even as simple as oat flakes and water.

Our interest in this organism as a material for interactive devices is inspired by its unique biological properties, which have been explored by researchers focused on engineering living circuitry, namely Whiting et al. [71] and Adamatsky et al. [2]. We primarily leverage two unique characteristics in our design: (1) physarum are extremely effective in growing towards food sources [53]; and, (2) they can conduct electricity [4]. Moreover, (3) they also react to other external stimuli including light, heat, touch, and chemicals [50]. These unique properties have led many to explore physarum as conductors [71] or as simple logic gates/sensors [2, 5, 72].

On top of the aforementioned technical reasons that make physarum a viable organism to be directly integrated in the function of an interactive device, we also designed around two additional unique properties: (4) they can thrive in a wide range of environments as long as a certain level of humidity is maintained and food is available [19, 30]; and, most remarkably, (5) unlike many other organisms, they can enter a dormant phase if environmental conditions are not adequate for life (namely food and humidity). This dormancy phase can last long periods of time (on the order of years) and can be reversed if the environmental conditions become again suited to life (i.e., in general, they resuscitate from dormancy with the introduction of moisture and food in the surroundings) [37]. These latter two properties also influenced our choice of slime mold as a suitable candidate for exploring physical care interactions inside a functional interactive device. Their ability to enter a dormant phase allows us to leverage some of the benefits of virtual care (i.e., the virtual pet never really dies and can be suspended) while benefitting from the advantages of a living organism, i.e., it physically reacts to care/food, etc.—which we hope influences the relationship between user and device by adding a sense of responsibility. And last, due to their variable size, they can be incorporated into a small wearable device or used in large displays [46, 61].

Importantly, we acknowledge that introducing a physical organism in the function of an interactive device is not without technical limitations. Organisms display a range of disadvantages compared even to a simple copper trace (e.g., requiring food, instability, fragility, uncertainty of growth [3, 64]). However, our focus is on the benefits of introducing a physical organism in the function of an interactive device, in other words, in the added friction from the physarum (as any living organism) requiring an environment conducive to life, which in our concept the user is responsible for providing.

Finally, while there have been explorations into the potential of physarum as conductors or sensors in a circuit [3, 5, 71, 72] ours is the first to explore utilizing this organism inside an *actual* everyday interactive device, such as a smartwatch.

3 OUR CONCEPT: CARING FOR INTERACTIVE DEVICES BY INTEGRATING LIVING ORGANISMS

We present our concept of implementing physical care in interactive devices by integrating a living organism in the function of the interactive device. Figure 1 depicts our concept through our smartwatch prototype. In this prototype, the user delivers the physical care by giving the slime mold water and oats. If the organism thrives, its growth becomes electrically conductive and acts as a circuit wire enabling functionality in the device. In our concept, much like friction-based UIs, the care is not relegated to the background but instead, becomes an immediate aspect of interacting with the device. This reminds the user that this kind of interactive device is not made only from inert materials, but that *there is a living organism integrated with it.* While caring for this device, users experience real consequences, including that the organism might go dormant or die if they do not create a favorable environment.

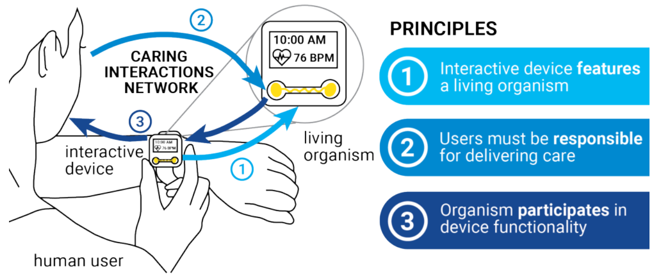

Figure 3: A visual depiction the three principles key to our concept via the example of our slime mold smartwatch.

While our prototype takes the shape of a smartwatch, we recognize that many other forms/designs can realize our concept. As such, in Figure 3 we depict the three key properties that are required to instantiate our concept: (1) the interactive device must feature a living organism, (2) users must be responsible for delivering care, (3) organisms must participate in the device's functionality.

Principle 1: interactive device features a living organism. Our concept relies on qualities evoked from interaction with a living organism, which might inspire a different quality than if the device was purely inorganic. It's difficult to feel kinship with materials when they are not as responsive as organisms. Whether plants, fungi, bacteria, animals, slime mold, or humans, all need the right environmental conditions to thrive. Thus, living organisms offer many material qualities that create high stakes (quite literally life or death) if the environment they inhabit is not conducive to life.

Principle 2: user is responsible for care. While there are many systems that can provide care automatically (automatic watering/feeders or humidity-controllers), our concept puts the users in charge of the act of care. If an automated system would handle the care for the user, it could quickly fall back into the sort of virtual care relationships created where delivering care is a frictionless experience (i.e., a push of a button in a virtual environment). In requiring the user to perform care, the user also becomes a partner in this relationship between user, device, and living organism.

Principle 3: organism participates in the functionality. To further encourage care, the state of the organism must correspond

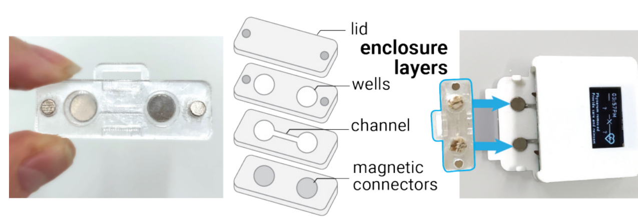

Figure 4: An overview of the physarum enclosure showcasing the layers and how it reconnected to the device via magnets.

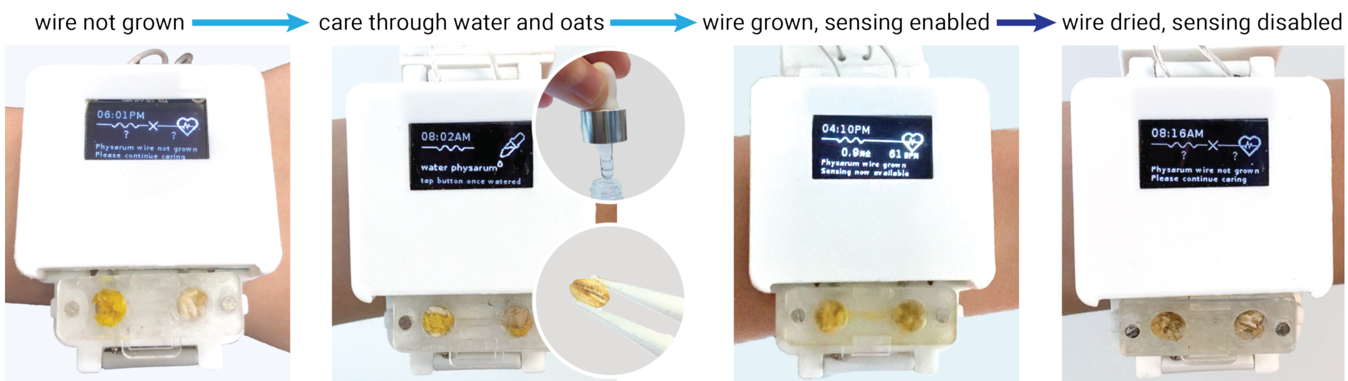

Figure 5: Stages of interaction embedded in our smartwatch device: (a) the wire is not grown; no heart rate is available. (b) the user "cares for the device", by caring for the slime mold (feeding it water and oats); (c) when the slime mold becomes healthy, it conducts electricity and enables the heart rate sensor; (e) if the user neglects to care, the slime mold dies and disables the sensor.

to some aspect of the interactive device's functionality. This could take the form of conducting electricity inside the device's circuit (as in our smartwatch), forming an essential structural component of the device, or any other means to enable a functionality. Moreover, from the user's standpoint the way that the organism contributes to the functionality must be as explicit as possible. Thus, if the user immediately recognizes the impact of the organisms' health in the device's functionality, they can understand the impact of the care they deliver—offering more potential to deepen the user-device relationship.

Now, we explain how we instantiated these three principles and created a new kind of device by engineering a smartwatch that includes a living slime mold.

4 OUR INSTANTIATION: SLIME MOLD SMARTWATCH

We present an example implementation of our main concept, an interactive smartwatch that includes a slime mold as a living wire. As depicted in Figure 5, the heart rate is only enabled if the user cares for the slime mold so that it grows healthy and conducts electricity. If neglected, the slime mold dries up and becomes non-conductive, disabling the heart-rate sensor. To accelerate researchers interested in reproducing our device, we made it open-source[1].

4.1 Designing a Physarum Enclosure

We created an enclosure for the organism enabling the user to care for it (by delivering oats or water) as seen in Figure 4. This enclosure is designed to direct the organism's growth in a single direction. The enclosure is primarily made of clear acrylic but in each well, the bottom layer consists of a magnet. The physarum grows on one side of the magnetic surface, and the other enables a quick connection to the device's circuit. The circuit only becomes fully connected if physarum grows between both wells, through the bridge.

[1]https://lab.plopes.org/#integrating-living-organisms

4.2 Dormancy and Resuscitation

Slime molds have a reproductive cycle like most living organisms and reproduce via the formation of spores. However, one interesting aspect of the slime mold lifecycle is that they can (almost *immortally*) oscillate between a *living* and a *dormant* version of itself. Essentially, slime mold can be dried up and exist for years in their dormant sclerotium state. When environmental conditions become more favorable (with the introduction of food and water), they will be resuscitated and, therefore, reenter their "living" state. This cycle between living and dormant is fundamental to our interaction design, and we focus on interacting with the physarum in between these two states as seen in Figure 6.

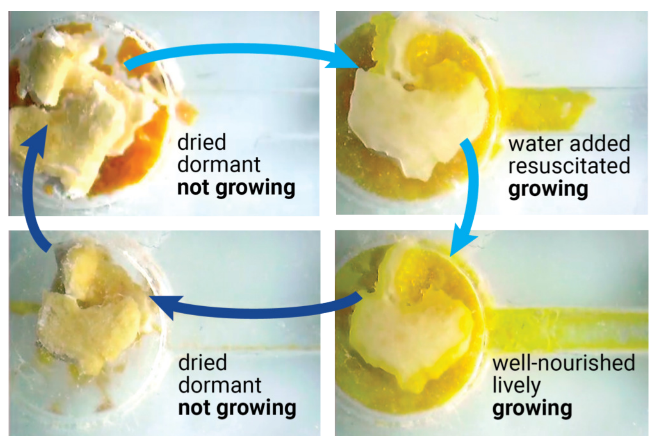

Figure 6: Photographs (7.5x magnification) of a slime mold oscillating between living and dormant stages.

4.2.1 Implementing a Care-based Interaction. One of our principles is making the care immediate and clear to users. Thus, our enclosure's lid is **transparent** so that **users *always* see the slime mold** and, moreover, it allows for caring for the physarum by: (1)

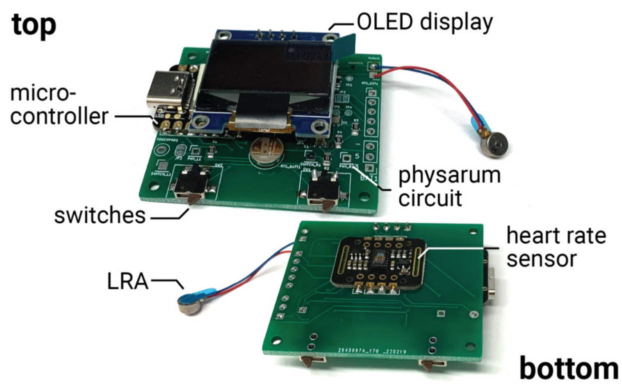

Figure 7: An overview of the main electronic components embedded in our slime mold integrated smartwatch.

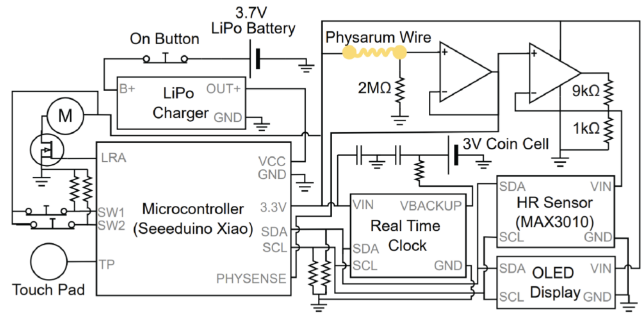

Figure 8: Schematic of circuit implemented in our smartwatch.

removing the compartment, (2) feeding it or watering it by dropping oats or water into the wells under the lid; and (3) reattaching it.

In addition to enabling care, we further encouraged users to care for the physarum by incorporating the state of the physarum's growth into the functionality of the smartwatch device. If the physarum has favorable enough conditions to grow a wire, it can conduct electricity along that wire. If current can pass through the physarum wire, the heart rate sensor that is embedded in the smartwatch receives power, enabling the user to see heart rate data and the resistivity of the physarum wire. We opted to associate the heart rate sensor functionality to the physarum growth as a symbol of livelihood between both user and physarum.

4.3 Electronics Design

The device itself consists of a custom PCB, depicted in Figure 7, which integrates: (1) our physarum sensing circuit (described below), (2) an SSD1306 OLED display, (3) an Seeeduino Xiao microcontroller, (4) a MAX3010 heart rate sensor, (5) a RV-3028 real-time clock, (6) a linear-resonant actuator (LRA), and (7) a 3.7V 200mAH Li-Po battery.

The microcontroller (SAMD21 Cortex M0) communicates with most sub-components via I2C (display, real-time clock, and heart-rate sensor), except with the LRA, limit switches and the physarum wire. To allow users interact with the device, besides the display, we also provide touch input, vibration output and detection of the physarum enclosure removal. We realize the touch input using a capacitive sensing pad, embedded directly on the 3D printed enclosure, which is sampled by the SAMD21's internal QTouch firmware. To deliver vibrations, we actuate the LRA using a MOSFET (SSM3K15ACTC). To detect if the user removed the physarum enclosure (and to encourage them to put it back) we added two surface-mounted limit switches (JJJHLGG200NOPMRTR) sensed by the microcontroller via a pull-down circuit. Finally, so that the smartwatch's display can depict not only the physarum's wire state (described below) but also the current time of day, we integrated a custom-designed real-time clock using the RV-3028. Even if the main battery (3.7V 200mAH Li-Po battery) is drained, the real-time clock dynamically switches to a backup small 3V coin cell battery (directly soldered onto the PCB) which keeps the time accurately until the main battery (and thus the microcontroller) become operational again.

4.3.1 *Physarum wire circuit design.*

We engineered a circuit so that when the first physarum wire was formed across the two electrodes, it would enable power to the heart rate sensor. Thus, the state of the physarum wire corresponded directly to whether the heart rate sensor was powered. Additionally, we also sense the resistance of the physarum to provide feedback to the user about its state. To accomplish this, we designed the circuit shown in Figure Figure 8. This circuit implements two functionalities: (1) it provides a resistance sensing over a 2MOhm voltage divider, which are then fed into an opamp (MC33202) in a voltage follower configuration, allowing the microcontroller to sample the current value of the physarum wire; and (2) a subsequent opamp (MC33202) in a non-inverting amplifier configuration, the output of this is directly fed to the heart rate sensor. The resulting effect is that if the physarum wire is grown across and healthy (conductive and less than ~3.5MOhm resistance) it will power the heart rate sensor module. This was specifically designed to be not a *software enable* but *baked onto* the hardware.

5 TECHNICAL EVALUATION OF OUR LIVING WIRE

Choosing a substrate. As with any living organism, growing healthily requires favorable conditions. At the same time, physarum can withstand many conditions and can rapidly grow given food and adequate humidity. We tested growing physarum on a variety of substrates, including agar, metal, paper, cloth, and plastic (PLA, acrylic). We found that they were able to grow across all these surfaces with minimal variation. As such, in our device, we chose to grow ours on plastic and metal (for the electrodes).

Choosing nutrition. In nature, physarum consume types of yeast, bacteria, and fungi. Oats present a convenient substitute for these foods. Via months of testing and growing dozens of physarum, we found that providing oat flakes moistened by water and adding an additional one water drop about two times a day was adequate for encouraging physarum wire growth across our enclosure.

Wire formation speed. To observe the speed of the physarum's growth, we conducted a series of time lapses (taking a photo per

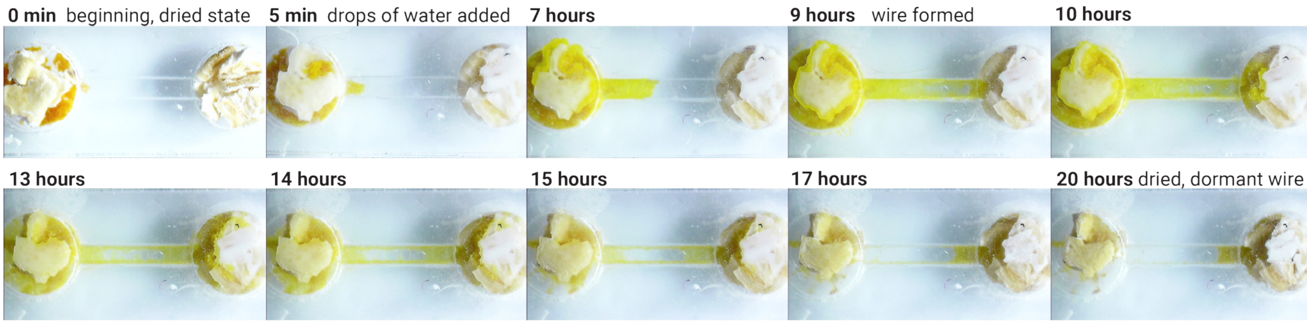

Figure 9: Photo captures from a timelapse of one physarum wire growth over the course of 20 hours.

minute) of the physarum's growth and drying out in our enclosure. We found that across three trials, it took about 12.67 hours (SD=3.05) to form a wire and 16 hours (SD=9.64) for the physarum to break its wire without oats/water. After oats/water were reintroduced, it took approximately 10.33 hours (SD=4.93) for the wire to regrow. One of these timelapses is annotated in Figure 9.

Light influence. Physarum also prefer to grow in the dark and while we did not incorporate this into our design, we encouraged users to allow them to grow in the dark when not wearing the device. To test the impact of light, two physarum petri dishes were placed directly under a light source; one covered. We saw negligible difference between the two in terms of growth and ability to resuscitate them.

Physarum's resistance. While previous work characterized the resistance across a *single* physarum wire strand [3] (i.e., an extremely thin physarum wire), we found that our enclosure resulted in different resistances across the wire. This is likely due to two factors: increased wire formations (especially in parallel) significantly change the resistance, or residual water during care modifies the resistance. Thus, we characterized 12 physarum samples grown inside our enclosure, and measured their resistance every 8h after one single initial care routine; then, no more care was provided, and we measured how the resistance changes once they dried up. Resistance was measured using a resistance-measuring circuit [65] and a high-precision ammeter (6.5 digit, 1nA accuracy). Figure 10 depicts the results, which as expected, demonstrate how the physarum wire resistance dips once a wire has formed and gradually increases as it dries. These measurements were conducted in laboratory conditions: container was closed and non-moving, kept at a stable temperature and only exposed to light during measurements.

Variability of living wire. As with all organisms, there is variability in growth that cannot be fully controlled. While we presented this technical evaluation to give readers an approximation of what they can expect when working with living wires, ultimately their growth is not deterministic and can only be guided or nudged. Variations in growth are typically caused by available space, light, humidity, temperature, chemicals, etc. While all factors cannot be controlled inside a smartwatch, our approach aimed at controlling one factor specifically: available space for slime growth. We guided growth using our tunnel-like structure. This ensured our device could grow slime molds in a more repeatable and similarly timed manner across different runs.

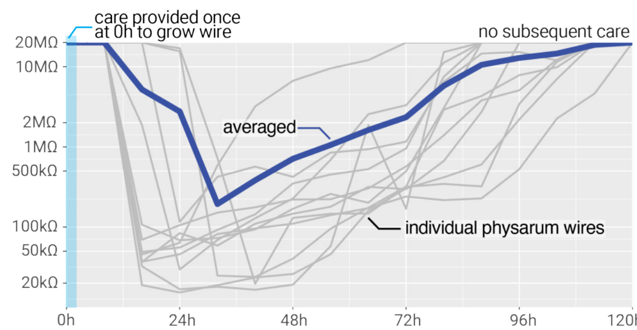

Figure 10: Resistance measurements (log scale) over 120 hours.

6 USER STUDY: PERCEPTIONS OF A LIVING WEARABLE

To explore how users perceived a living wearable device that must be cared for, we conducted a user study (in Figure 11), where we handed over our smartwatch to five participants and asked them to wear it for 9-14 days (depending on interview scheduling and speed of wire growth/drying).

We designed this study so that participants would experience two distinct phases while wearing our smartwatch, which we depict in Figure 11 (1) **caring phase** (initial resuscitation of a dried physarum until full growth of wire); and, (2) **neglect phase** (after interview 1, participants were instructed to stop caring for the physarum until dried and nonconductive)—this allowed us to collect feedback from both caring and non-caring stages. Through their daily entries and interviews, we collected accounts of what feelings, perspectives, and thoughts emerged from participants as they interacted with this device. Our study was approved by our ethics committee (IRB20-0290).

6.1 Participants

We recruited five participants (average age: 30.4, SD=11.06; all participants identified as women) from our local institution. Participants were compensated with 100 USD.

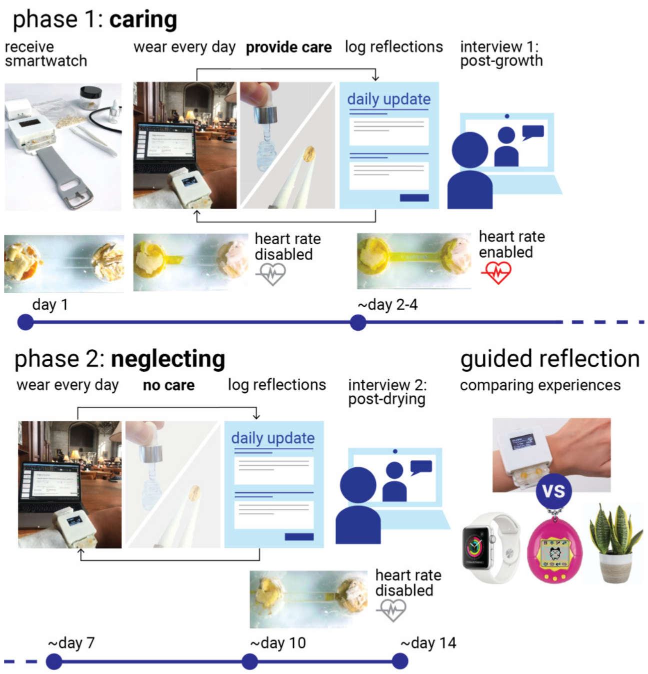

Figure 11: An overview of our study structure with a timeline of major events in the study: caring phase and neglecting phase.

6.2 Apparatus and On-boarding Instructions

Apparatus. Participants were provided our slime mold integrated smartwatch and materials for care (water dropper and oats). The physarum wire enclosure was pre-loaded with dried physarum in one well and oats in both wells.

Onboarding. Participants were instructed to wear the watch for as much of the day as possible. We explained how to care for the physarum and how to use the smartwatch. We instructed to care for the slime mold by providing one water drop twice a day and oats every two days. Whenever not using the device, (e.g., during sleep), we asked that they kept it in a darker environment. Our device additionally provided reminders (via its display and through vibration) to water the physarum every four hours (i.e., twice during daytime, not at night) and to feed the physarum every two days. Finally, we provided two recommendations in the event of more extreme circumstances: (1) wearing the watch under a sleeve during extremely cold weather; and (2) scooping out any contaminated growth and provide more oat and water (only happened once during our study).

6.3 Study Procedure

Daily feedback. Participants filled out daily update forms. The update form asked for the physarum status, the type of care they gave to the physarum, a picture of the device, and notes on any reflections or experiences they had on that day.

Interview 1: post-growth. Once participants grew a physarum wire and had a heart rate enabled watch device, we interviewed them by asking general questions about their experience and follow up questions from their diary entries. After this interview, we instruct them to not care for the physarum (no longer provide water and oats) but to continue wearing the device and filling out daily entries.

Interview 2: post-drying. Once the physarum was dried and no longer enabling the device's heart rate sensor, we conducted a final interview and concluded the study. This final interview had two halves: in the first half, we asked general questions about their experience in the same format as the first interview; while, in the second half the experimenter we asked more questions about the type of care they performed and how it related to their other experiences with living organisms and devices. As part of this second half of the interview, we also asked participants to engage in an exercise to imagine future physarum devices.

This study structure was designed in a way that allowed participants to freely provide feedback and minimize the chance of experimenters biasing participants with specific questions on specific topics, i.e., in all our daily feedback forms, first interview and the first half of the final interview, there were no direct questions on specific topics or mentions or specific topics made by the experimenters. Only in the second half of the final interview, the experimenters explicitly asked more directed questions.

6.4 Results

Using participants diary entries and transcribed interviews, the first author conducted an open coding of materials and themes were constructed and further revised by all authors. The goal was twofold: (1) cluster similar accounts, (2) identify in which stage of the study this account was elicited. We organize participants responses into three sections: (1) caring phase – from initial receiving of device, growth of wire, to first interview, (2) neglecting phase – after first interview, not caring for the physarum until it dried, and first part of last interview, (3) guided reflection– second part of exit interview, which marked the only moment where researchers asked direct questions about how this experience was different from previous interactions with devices.

6.4.1 *Observations from phase 1: Caring Phase.*

On average, participants took 4.4 days (SD=3.43) to grow a wire and participants engaged in caring for the physarum for an average of 7 days (SD=2.82) before their first interview. During this interview, the experimenter asked general questions about the experience of wearing the device (what difficulties they experienced, if their perception changed over time, etc.) and asked participants to further expand on their submitted daily updates. These accounts of participants experiences are clustered and summarized below.

Fascination with the organism. For all participants, this was their first experience interacting with a slime mold. The novelty of wearing a device that housed a slime mold was expressed by all. P2 stated, "[at the start] I don't even believe that they're alive, so when I give them water and oats (. . .) that is the most exciting part, seeing that they actually ate the oats and keep growing made me feel very, very excited." Moreover, all participants reported that they "showed off" their device to friends and coworkers during this phase. In recounting a family dinner where the device and study became a topic of conversation, P4 explained "I think it piques a lot of people's curiosity and imagination".

Care strategies. While participants were provided the same care instructions, they adopted various strategies. P1 initially wrote down the care in her notes, but this gradually settled as a routine. P2 and P5 used visual observation to decide when care had to be provided. At one point without experimenter instruction, P2 added more dried physarum (which was provided as a backup) into the well to encourage growth, explaining that "they could support each another". P3 relied on the care reminder alerts, noting that these reminded her that "it had these needs and it felt more like a real thing even though it was just like an alarm clock going off (. . .) more real and alive". P4 described her process of learning to care for the physarum as a "lesson in responsibility".

Friction while interacting with an organism. During this phase, participants also experienced several moments of friction. For some, this arose from a lack of control over the physarum. For instance, P3 experienced moments of friction due to the aesthetics of the living organism stating, "I suppose it is a living thing so I can't expect it to be not as messy". The responsibility for the physarum required from participants also appeared as a source of friction. During the study, P5 had a fever yet still provided care for the slime mold, explaining that she felt "worried about whether their slime would be okay" even during her illness.

Developing a connection. All participants expressed various feelings of connection with our device. P1, P2, P4, and P5 all described it as a little friend and/or pet. P2 expressed, "it's always good to be accompanied by some living creature, I really like different, animals or plants. (. . .) carrying this little friend also made me feel happy and peaceful". P4 noted that she would be reminded by the slime mold's presence by its smell, even stating that it felt endearing, "my cat's kind of have a smell, dogs have a smell, the physarum, I recognize the smell and it smells kind of, organic, it's kind of yeasty but not like decaying, it smells alive". In recalling an experience where she had to take a long drive, P4 explained, "oh, I gotta bring my little pet mold friend, during the drive, I was also thinking about how I used to be really into Tamagotchis (. . .) with the physarum, (. . .) it has this smell to it which your Tamagotchis don't have, it has a sense of physicality, (. . .) they're definitely different". P1 stated that their personal care routine ended up linked to the device's care routine "I think every time I fed myself is when I would remember to at least check it, I think that was actually quite linked". While she was sick, P5's partner helped take care of her as well as helped to take care of her device. P5 recounts, "I was taking care of the slime and feeding it oats and stuff, my partner was also feeding me oatmeal because I was sick and so she was like you're my little slime and I was like yeah, I am (. . .) then she started calling me her slime because I mean me and the slime, like, we were eating the same stuff, (. . .) we were both being fed and watered". P2 & P4 also stated that the visual appearance of their device affected their mood. P2 explained that growth made them feel refreshed. P4 associated the bright yellow of the physarum with happy feelings, noting this affective quality several times in her diary entries and in her interview.

6.4.2 Observations from phase 2: Neglecting phase. On average participants took 1.8 days (SD=1.3) to dry their wire and they were in this neglecting stage for an average of 5.2 days (SD=1.09) before their closing interview. The experimenter asked general questions about the device and asked to expand diary entries for this phase. We also asked if participants could imagine themselves wearing a device like this in their daily life.

Transition to neglect. After being instructed to neglect the physarum, participants varied in how much they struggled to transition. All participants expressed that there was less work involved with our device when neglecting vs. caring, citing that they did not have to think about the device as much. P1 stated, "I felt kind of relieved that I didn't have to take care of the watch anymore, but at the same time I was super surprised at how quickly it stopped sensing". P4 described the transition as "kind of a mindset shift like. . . now I just don't need to take care (. . .) I think the on the responsibility side, [I] kind of let loose and I detached a little bit from feeling really connected." All participants also expressed feeling sadness or guilt in the process of neglecting the slime mold. As a note, many participants referred to the dried slime mold inside their watch in this state as "dead", despite technically being in "dormancy" as it can be resuscitated. In fact, the physarum inside their smartwatch at the start of the study had been in dormancy before their initial care.

Change in interaction. All participants expressed that their interactions with the device changed during neglect. One of P1's diary entries indicated "[I] completely forgot to wear the watch today (. . .) not having to take care of it (. . .) has made it harder to check up on it and wear (. . .) [it] is now definitely dead". Additionally, she expressed, "I think it became more like a normal watch". On the other hand, P2 had a very different experience where she decided to avoid looking at the dried slime mold, stating "[it] made me a little bit sad". Also, while she had excitedly introduced the watch to others during the first stage, she didn't show off the watch in this stage and expressed anxiety over having to explain its dried state to others. P4 noted that "[during the growing phase] I felt motivated to keep it on and check up on it a lot, but not having to do that, I kind of treated the watch more like an object". Similarly, P5 explained "I didn't feel like connected to it really, in a way I was just kind of like, yeah, there's nothing special about it. Now, it's just like a watch, so you know, there's no purpose of caring for it".

Would you wear this device? When asked if they would wear this type of device, participants had varied answers. P1 said she was split as she enjoyed it more when at home taking care of it, but outside she felt responsible for the physarum's wellbeing in the cold. Similarly, P2 expressed that she might want to wear the device for about a week, but "after that, I think it's the same feeling when you have a pet, you like his company, but you don't want to take the risk that he gets ill or dies". P3 expressed that they would be more interested if it featured another organism "like a plant". P4 expressed that she would as she found learning how to care for the organism fun. P5 explained, "I would be happy to wear it especially if I was taking care of it, it can serve as a nice reminder for myself to get a drink of water or something".

6.4.3 Thematic Questions. In the final part of our exit interview, we asked participants a series of questions to try to ascertain how their experiences with our watch different from the type of relationships they had previously encountered with devices, virtual pets, etc.

Regular vs. physarum-integrated watch. Both P1 and P2 wear smartwatches regularly during exercise. When asked to contrast the experiences, P2 stated "the [regular] watch is only a tool (. . .) I don't need to take care of it, it will not turn grey or need extra care, so it's totally different (. . .) right now, if you asked me to draw a picture of it [their own smartwatch], I can't, but for this [physarum] watch, I can draw every detail". P1 similarly described smartwatches as tools when comparing experiences, explaining "[a regular smartwatch] is supposed to help me reach a goal, (. . .) but the other [physarum] watch felt like this is some [thing] I had to take care of, so it was like it wasn't a one-way relationship, I was taking care of it, and it was like giving me the time or a heart rate like as pay back, so it was like bi-directional". P4 wore a watch in the past for a short period of time and compared the two by stating "I think the normal watch was definitely easier to have mindlessly on. With the living smartwatch, I was actively thinking about it, and while I was taking care of it, was monitoring [it]". P5 never regularly wore a watch device before but contrasted her experience with other devices by explaining, "other pieces of technology. I would say I have an ambivalent relationship with them. I don't care a ton about them. I don't negatively or positively think about them, whereas I did think both positively and somewhat negatively about the slime".

Virtual pet vs. physarum-integrated watch. While we did not screen for participants with prior experience with virtual pet interfaces, P1, P2, P4, and P5 had previous experiences. P3 had previously worked with kids and observed play with Tamagotchis. When asked to contrast the experiences, all participants cited the *physical liveliness* as the most significant difference but commented on different qualities liveliness brought to their experience of care. P1, who had interacted with *Neopets* (a website where users can own and care for virtual pets) explained how the physical presence of the physarum on our device made her more conscious of the care they needed compared to Neopets, which could be easily forgotten for weeks. P2 contrasted caring for our device with her experience taking care of her *Sims* (a game where players care for virtual humans). She stated that the experience "is quite different because the physarum are not virtual, even though they're attached with the electric device, the watch, but [the physarum] itself is not virtual. It's real (. . .) in the [Sims] when your character die, you just create a new one without any effort, you just click the button, and then a new character is born and then everything is as usual, but this [physarum], you need to take extra care." Similarly, in recollecting what she observed with Tamagotchis, P3 stated, "with something like a Tamagotchi, it was programmed to work pretty logically (. . .) but with organisms there's more uncertainty it may not live or grow even if you did all the right things". P4, who also had previous experiences with Tamagotchis, various web-based pets, and a robot dog toy, stated "I felt like I had to be a little more responsible with the physarum, because with a virtual pet, you can just kind of neglect it and then come back to it (. . .) having some experience with real pets makes me more reluctant to neglect things, I felt more responsibility for it because if I was that way with my cats that would just that would not be okay".

Care for other living things vs. physarum watch. All participants had previous experiences in caring for living organisms whether plants or pets. P1 found the experience quite different to taking care of her houseplants stating, "they're stationary things that you have a schedule [for] and you take care of them, and you are only aware of them when you're at home. I don't ever think about my plants when I'm not home. That's not really a worry that I have (. . .) I feel like it's closer to having a dog than having a plant because you gotta walk your dog (. . .) I think that level of concern you feel about a dog interacting with the world is maybe, at some small level, like the concern that I had for the watch being exposed to the elements". P3 felt the process of caring for both the physarum and her garden plants was similar in the level of uncertainty it involved because she's "not exactly sure how much to water them, how much fertilizer to give (...), so it had a lot of similar uncertainty, you don't have total control over it". P4 equated the processes of learning to care for plants, her pets, and the physarum in a similar manner.

Care for electronic devices vs. physarum watch. We asked participants to contrast the care they gave to their electronic devices (repairs, maintenance, cleaning, etc.) to the care they provided to their physarum-integrated watch. P1 explained that the care felt different because of the similarities between physarum's needs and her needs, "giving water and oats, which are also things we give ourselves, like I eat oatmeal, and I drink water, it feels more like an animal or it is a living thing (. . .) the fact that I give it nutrients that I also give myself that makes it even more like a living thing". P2 also noted a difference, "this smartwatch, I feel I'm connected with it, because it has the living part and we can build the connection very quickly, from the first day, I start to be connect[ed] with it, but with my device, it might take years to build the relationship". P4 stated that there were different stakes at play, "I don't think of charging my devices as like feeding them, whether they need it to survive or thrive, it's kind of the same no matter what (. . .) but with the physarum, you can tell if it's more or less happy (. . .) I guess I was more concerned about the well-being of the physarum than I would be for an electronic device". P5 noted that "during the [caring phase] it definitely felt like more of that urgency (...) I'd say I was more motivated to care for it on a daily basis than I would be other electronic advice devices."

How would you dispose of the watch? P3 stated that they might dispose of the watch itself but keep the physarum. P2 stated she might "sell the watch so that it wouldn't be left by itself and someone else could enjoy". P4 stated that she would try to pass on the device, "I think I would just try to show it to a friend and pass it on (. . .) if you really couldn't take care of a pet anymore, you would try to rehome it". P5 felt unsure and even stated that she had been wondering before being asked this question, stating, "I have no idea, because I always feel like I don't know what to do properly with technology anyway, like, how do you even get rid of technology? (. . .) I would probably feel really bad throwing the slime away, so I don't know what I would do".

Future version? When asked to imagine a next instantiation of a physarum-integrated device, P1 envisioned a child's night light or a solar panel with a physarum; P2 envisioned a vase with a physarum; P3 envisioned the physarum inside the circuit for an indoor fan, something she would "keep next to her window and plants at home"; P4 provided two visions: one in which the physarum assists in an interactive device that communicates the needs a tree has (suggesting enlarging caring relationships to another organism), and the second in which a physarum grows and connects to multiple points on a music synthesizer's circuit board, enabling the creation of sound; finally, P5 envisioned a device with "emotes for the slime mold", enabling it to express happy or sad states.

6.4.4 Summary of Findings. We discuss the specific topics we noted in reviewing participant accounts of their experience.

Sense of responsibility. Over the course of the study, participants exhibited a sense of responsibility for the device. This was most pronounced during the caring stage. Additionally, participants adopted various caring strategies that even included protecting the device from external factors they thought would damage it (e.g., cold). This was also demonstrated by the struggle some participants felt when we instructed them to neglect the physarum. Last, participants comments depict how the fact that the device was dependent on the participant's care and contained a physical living being gave them a sense of responsibility that was distinct from virtual pets or their other devices.

Affinity to organism and reciprocal relationship. Almost immediately, most participants started to refer to their physarum as a little friend or pet and explained how they liked the company of another living organism. Participants often described a feeling of relatedness in providing water and nutrients, which humans themselves also required. An example of this is how, at times, participants connected their own self-care to the physarum care. This affinity towards the living organism in the device was even more pronounced when participants were asked to contrast their experiences with other nonliving devices. Participants described the livingness as a quality that allowed for a faster connection whereas connecting to their devices often took years. Additionally, participants described their relationships to their devices as one-way or merely functional. On the other hand, with the physarum integrated watch, the relationship felt more "bi-directional", as P1 put it.

Affective responses to device's state. Throughout the study, participants described emotional reactions to the state of their device. Even qualities like the color of the physarum or the smell of the physarum drew out emotional responses. Participants also expressed feeling attuned to the physarum and as if they experienced empathy towards the physarum.

Study limitations. We also acknowledge that our study findings come with their limitations. We focused on studying a specified interaction cycle (dried/dormant with heart-sensor disabled, to healthy with heart-sensor enabled, and back); to create this cycle we requested that participants halted care for the device. However, future studies might elicit different responses without a prescribed "neglect" phase. Also, as with most studies of this type, our findings might exhibit some degree of novelty effect as participants have never experienced such a device. Furthermore, this limits how much we can extrapolate about users' physical caring experiences vs. virtual care. A prolonged study might offer additional insights, after the novelty wears off. Our prototype is also not as "polished" as a commercial smartwatch, creating additional frictions during use. For ease of care, we designed the physarum enclosure as removable, but a different design where the physarum enclosure could not be removed might also afford different responses. In the user study, the slime mold was exposed to a number of unpredictable external factors that could limit growth (light, cold/dry air, participants occasionally forgetting to water, etc.). Due to this, there was likely some variability in growth that could not be controlled. The cold climate the study was conducted in (February-March in the Midwest United States) may have also affected slime mold conditions. Future studies will be needed to determine viability of wire growth, particularly in extremely hot and dry climates. Last, as our user study consisted only of women, we note that our findings are implicated by gender. Our participants often cited experience with toys (often marketed towards young girls) as part of their interest in the study and care work itself is often gendered labor. While not a focus of our work, the role of gender in care relations for living media interfaces should be explored in the future works.

7 DESIGN RECOMMENDATIONS

For others interested in expanding our work and instantiating their new care-based interactive devices featuring organisms, we reflected on our experience to provide two sets of design recommendations: for slime-mold interactive devices and for future care-based interactive devices using other organisms.

7.1 Collaborations with Slime Mold in Interactive Devices

During our process of working with slime mold, we were constantly inspired by the organism and influenced by it.

Aesthetics. In our work, we displayed the slime mold in a clear enclosure so that users would be able to see their physarum's growth as much as possible. Their enclosure also came with a removable lid, allowing for easy access so that they could touch and smell the physarum too. In our study, participants all noted these aesthetic qualities of their physarum during their experience, often correlating it to their emotional response to the physarum or as a reminder that the physarum is indeed, alive. As such we recommend designers make these aesthetic qualities of the physarum accessible.

Responsiveness. Physarum have been shown to respond to a wide variety of other stimuli too including light, heat, and chemicals. Interactions could be designed to incorporate guiding growth by engineering attractants and repellants.

Lifecycle. The lack of immediacy and degree of uncertainty involved in relying on physarum as a functional component of an electronic device should be mindfully incorporated in the interaction design. Designers can even celebrate this aspect by emphasizing how functionality of a device only needs to be present for certain periods of time and that sometimes access to the functionality ought to be limited (i.e., taking breaks from seeing your heart rate).

Sharing organisms. Physarum can easily be shared and regrown whether in their lively diploid state or dried sclerotium. As such, interactions can be designed so that users can share healthy organisms, creating a communal experience with multiple physarum, users, and devices.

8 FUTURE CARE-BASED INTERACTIONS FOR LIVING DEVICES

While we focused on one instantiation of our concept (the living smartwatch), it can take many forms and generalize across different devices. We provide recommendations for future care-based devices featuring a living organism.

Mutual symbiosis. Fundamental to our concept is a care-based relationship. We encourage designers to think beyond the human in a "user" role (a one directional, extractive relationship), but as an agent that gives back as a caretaker. We also encourage designers include mutualistic symbiotic relationships as these promote a bidirectional sense of relationship, rather than the traditional "user of this device". Notably, our instantiation is not a truly mutually symbiotic relation as we do take the slime mold out of their natural environment for our purposes.

Uncertainty. Living organisms are not as determinate as the traditional inert materials often used to make interactive devices. This creates some difficulty in designing with them, but also enables more diverse, surprising states due to the uncertain way they respond to external factors. This quality should be celebrated in interactions with living devices to encourage new relationships beyond expecting devices to be easy, fast, reliable, and purely at our disposal.

Showcase the organism. In an interactive device that features a living organism, the device's form factor and interactions should highlight the qualities of the organism. Rather than design devices that "black box" their inner workings, the organism's state and contribution should be made immediate. Thus, the organism's involvement is not overshadowed and feels more like a partnership.

Sustainability. Designers creating care-based devices with living organisms should always engage sustainably whenever possible. This includes using ecological friendly or compostable materials, disposing materials properly, considering ecological impact, etc. While this work focuses on care for a living organism and device, caring interactions should and can expand to the larger environments and ecologies we are a part of.

9 CONCLUSIONS & FUTURE WORK

We explored care-based interactions by integrating living organisms in interactive devices. We instantiated this by engineering a smartwatch where a user must care for a slime mold so that it grows a wire that enables a heart rate sensor. We evaluated it through technical evaluations and a study where participants took the device home. Findings illustrated that the living nature of our device created friction but also allowed for a sense of responsibility, development of a reciprocal relationship, and a variety of affective responses. Our work highlights how designs around care can change the relationship between users and their interactive devices.

Future work & integrating other approaches. Designing for experiences that foster more reflective relations between human user, devices, and other organisms has gained interest in HCI [47, 51, 57]. As the number of consumer devices exponentially increases, the toll on our environment becomes more pronounced. We see our approach as one way to encourage users to reckon with this aspect of their device use. Rather than a user-device relationship built on extractive use, we encourage devices where the user takes on a caretaking role. This goal aligns with various other approaches by the HCI community to create artifacts to question our relationships with technology, and we hope that ours can fosters debate and inspires novel perspectives on this.

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