Theme Article: Pervasive Sustainability

Re-envisioning the role of a *user* in sustainable computing

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Abstract—As more and more computing technologies become pervasive in our daily lives, more and more e-waste is generated. And yet, when designing the next generation of devices, we prioritize for qualities such as speed, usability, and usefulness (a.k.a. user-centered design), rarely exploring options that might not optimize for users but, instead, improve long-term environmental sustainability. Exploring these alternatives is essential for transitioning towards a more sustainable future in computing. To this end, we argue that the envisioned roles we attribute to users during user-centered design should encompass much more. In addition to the role of the "user of a device", we can design for user-roles such as maintainers, repairers, and recyclers of interactive devices. We discuss this design shift through examples of two interactive systems we built to explore altering the role of the traditional "user" to that of caretaker and recycler. Finally, we discuss more roles that designs might explore for their users and how these roles can encourage users to take on responsibilities to support more sustainable futures for pervasive technology.

The past few decades have seen a rise in pervasive computing technologies in all aspects of daily life, from mobile/wearable devices to smart home technologies. However, as the pace of technological innovation continues to speed up, so does the rapid obsolescence of these interactive devices as new products replace older versions. This has led to massive amounts of e-waste in landfills, becoming the largest consumer waste stream in the world.[1] According to the United Nations Sustainable Development Goals Reports, in 2019, each person generated an average of 7.3kg of e-waste and only 1.7kg of it was properly recycled. This rapid churn of devices into e-waste reflects consumer electronics market trends but also the priorities that drive much of the latest technological innovations in the field of Human Computer Interaction. In fact, when we think about our relationship to interactive devices, we primarily think of ourselves as consumers. This encourages an extractive relationship, in which we use devices without much reflection of the larger impacts of our use, such as the environmental costs of ubiquitous computing infrastructure.

Some research efforts have aimed to lessen the ecological impact of interactive devices by developing biodegradable materials or reducing our dependency on batteries.[2] While these efforts are essential for a more sustainable future, we also need to explore alternative user-device relationships that promote more reflection, care, and responsibility for devices rather than just relationships built on consumption and careless disposal. Over 50 million tons of devices end up as electronic waste every year and that amount continues to grow.[1] If we hope to change this pattern and transition to a more sustainable computing infrastructure, we must look to how we can encourage people to take on roles other than just "users" of their devices.

THE ISSUE OF E-WASTE

Breakdown, obsolescence, and decay are an inevitable part of the electronics lifecycle. These are shepherded by rapidly changing consumer market trends, evolving technology protocols (e.g., USB standards), and even timespan limitations of components (e.g., batteries have a limited number of charge/discharges).[3] There is a plethora of reasons why computational devices stop being used and yet, we fundamentally lack design processes and technical infrastructure to transform these devices when we are no longer using them.[4] Often, these unused devices are simply collecting dust inside user's closets or improperly disposed of in waste streams, presenting challenges for circular resource recovery.[5] Even if they are sent to proper e-waste recycling facilities for resource extraction, such facilities have also been shown to generate large amounts of waste and pollutants.[6]

More recently, companies like Apple have incorporated buyback programs for people to trade-in their old devices so that they can be properly recycled. Similarly, Right to Repair advocates have been pushing for legislation to enable consumers to also have the tools needed for repair (rather than only allowing repair to happen through the business). This shift is important as it empowers the average user or consumer of devices to also play a role in reducing e-waste by seeing repair as an option rather than needing to buy a device anew whenever breakdown, obsolescence, or decay occurs. However, the average interactive device is still engineered and designed in ways that make it extremely difficult for the average person to feel comfortable repairing. As such, the priority of design is around the "user" experience rather than when a user needs to (inevitably) enter another role, such as repairer.

(UN)SUSTAINABLE COMPUTING

Pervasive computing's hardware sustainability crisis goes beyond e-waste. In fact, recent crises such as COVID-19 have shown us just how fragile the supply chains for electronics manufacturing systems are.[7] Manufacturers and electronics companies experienced significant stalls and delays in their schedule due to the lack of materials. Various engineers had to even resort to dumpster diving for needed components when they could not be sourced via the usual electronics vendors during the chip shortages.[7] Moreover, the rare earth minerals that are at the foundation of computational technologies, composing the chips that perform computational logic, have been increasingly difficult to mine and source.[8] Our relationship with technology has been geared towards an expectation that we will replace most of our devices every few years, but increasingly it's clear that this is an unsustainable model for our society. Endless growth and resource extraction/use will not be possible forever. If left to continue as is, these unsustainable practices will halt advances in pervasive technologies. Instead, we argue that we will need to transition towards a model where repair and maintenance of our pervasive devices and play just as central of a role as their innovation/invention.

BEYOND 'USER'-CENTRIC

So, what might a more sustainable future of computing look like? We argue that, in additional to improving "green" technologies, we should also reimagine the way we interact with our devices. Particularly, we argue that we need to focus on designing interactions that happen outside of their traditional scope of "use" and even outside the traditional lifespan of a pervasive technology (i.e., even when the device is no longer used), such as repairing, recycling, or reusing devices.

While much of human computer interaction research centers around the "user" as default, only considering "user"-centric interactions is limited. We can and should do more than solely use our technological infrastructure. In fact, many people practice a lot of caretaking, maintaining, recycling, and repairing. Moreover, our interactive devices can have complex lives beyond their primary user's interactions. They can be passed on to secondhand users, become upcycled in new projects, or even be repaired. Many dimensions of device interactions are forgotten about when we focus solely on the user experience.

This approach of going beyond "user"-centric design also can encourage us to think of impacts beyond human users (such as impacts to climate, biodiversity, etc.). Recently, HCI has also been interested in pursuing a more-than-human centered approach to interaction design, calling on designers to resist designing with the anthropocentric values that have perpetuated our current climate crises.[9] We also feel that this approach can be used to reframe device design as means of increasing their usefulness to us as human users, rather than device design that accounts for the device's lifecycle and its potential to become e-waste or as a pollutant.

We see human computer interaction as a key site for us to encourage interactions beyond simply extractive use of devices and instead towards more collaborative and relational exchanges with their devices. To do so requires us to go beyond 'user'-centric approaches and be more expansive in our conceptualizations of the roles we take on with our devices.

DESIGN FOR OTHER ROLES

Part of facilitating users to take on other roles means building the tools and designing devices such that they are able to do so. As such, we are often designing for interactions that don't typically exist between the average consumer and their devices. Doing this work means inviting a combination of tool-building and speculative design towards a more sustainable and collaborative relationship to our technologies. In that sense, we are inspired by how the "maker" movement has ushered in a huge wave of tools, resources, and interaction techniques to allow everyone to feel empowered to make and build devices.[10] Similarly, we invite readers to envision how similar movements could be geared towards encouraging other alternative roles. In this section, we briefly discuss two roles, (1) caretaker and (2) recycler, that we have explored in our work, showcasing interactive possibilities that emerged by centering these different roles.

FIGURE 1. This example depicts a design centered around the user as a *caretaker*. This smartwatch has a slime mold in its circuitry. Its design requires the user to *care* for the organism (by feeding and watering the integrated living organism). Without care, the organism will dry up and stop functioning as a wire for the smartwatch, disabling its heart rate sensor.

Role #1: user as caretaker

Conventionally, our interactions with devices are not designed to foster a sense of responsible ownership. Instead, devices are often taking care of things *for* us (e.g., monitoring our heart rate or steps). We wondered: what if the reverse were true? What if, instead, we took care of our devices? We explored this by envisioning the user as a *caretaker* of their device.

To design for this user-role (caretaker), we turned to embedding a sense of *liveliness* in devices to encourage users to care for them. Notably, in contrast to popular forms of *virtual care* (Tamagotchis, Nintendogs, Neopets, etc.), we necessitated *physical care* in the device design. This approach was useful as the type of care we extend to our devices is clearly different than the care we extend to other non-human counterparts like plants or pets. To harness this caring connection, we engineered a smartwatch that incorporates slime mold (a living organism embedded in the device's circuitry) that physically conducts power to a heart rate sensor inside the device, acting as a living wire.[11] In this smartwatch, the availability of heart-rate sensing depends on the health of the slime mold (Figure 1). With the user's care, the slime mold becomes conductive and enables the sensor. On the other hand, without care, the slime mold dries and disables the sensor and resuming care resuscitates the slime mold.

Importantly, we wanted to see users take on the role of caretaker. To investigate this, we conducted a study where participants wore and cared for our slime mold-integrated smartwatch for around two weeks. In post-study interviews, some of our main findings included how participants felt a sense of responsibility and developed a reciprocal relationship towards their device, often contrasting the experience to the relationships they had with their other devices .[11] For instance, one participant described how it was "[not 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".

Notably, our participants also expressed uneasiness over how they would dispose of their devices after use, one participant saying "[I would] sell the watch so that it wouldn't be left by itself and someone else could enjoy [it]". Another participant compared giving the device to someone else to what you might do with a pet saying, "if you really couldn't take care of a pet anymore, you would try to rehome it". Such alternatives suggest potentially more responsible caretaking even for after device use.

While our work explored the extreme example of caretaking (where the health of an organism and functionality of the device is dependent on provided care), this caretaker-based design can be applied to a plethora of other pervasive computing devices in different forms. Others have similarly aimed to elicit feelings of responsibility and reciprocity, through approaches like ensoulment, achieving heirloom status, and by simulating livingness virtually.[11-12] In all these cases, designs focus on different dimensions of engaging users as caretakers – allowing caretaking to become a meaningful and celebrated part of interacting with a device. Using the role of caretaker as a design lens may allow us to engage with users beyond extractive use (and negligent disposal) and pave the way for more conscientious and sustainable device ownership.

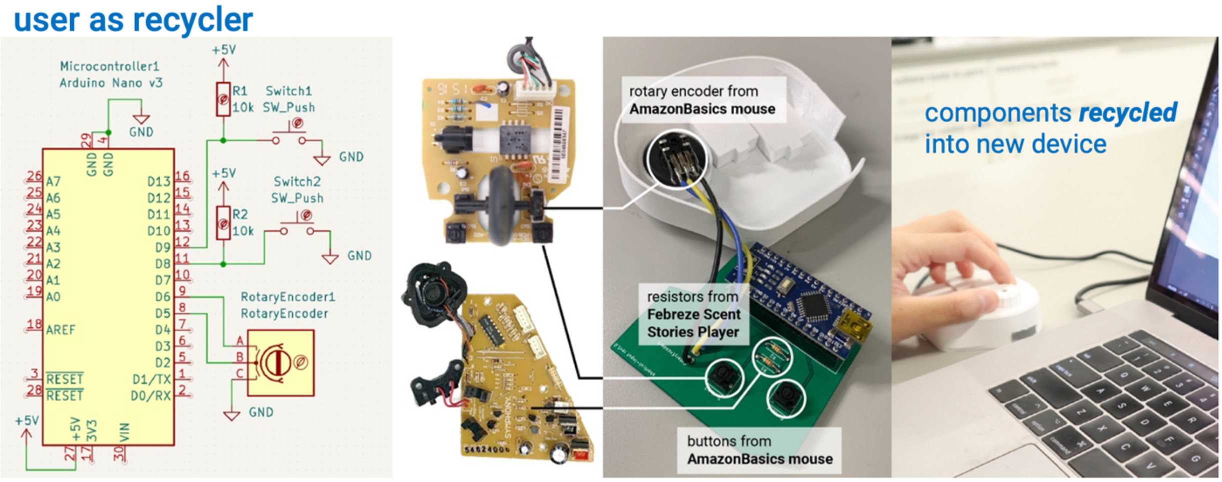

FIGURE 2. To support users as *recyclers*, ecoEDA is a tool that facilitates electronic component reuse during the electronics design process. This tool empowers users as recyclers to find solutions from scavenged parts in e-waste rather than buying components anew, reducing the amount of e-waste generated from the prototyping process.

Role #2: user as recycler

The issue of e-waste can often feel immense to consumers when options for remediation are primarily limited to opaque recycling processes. Additionally, devices are often sold to consumers as black boxes, but inside any electronic device there are dozens to thousands of electronic components, all potentially reusable in new electronics projects. We wondered: what if users saw devices not just as black boxes, but instead saw e-waste devices as potential resources? How could users begin to recycle their devices for new projects? We explored this by envisioning users as *recyclers* of their devices.

To design for this user-role (recycler), we looked at how electronics design processes could be oriented around the use of scavenged and found materials from e-waste. Currently, most electronic design tools assume that all electronic components will be bought anew, a process that can inevitably generate many rounds of e-waste through the prototyping process (i.e., in creating and assembling multiple PCBs). Additionally, there are many barriers to creative reuse and recycling of electronic devices. In short, there is a lack of tools and resources to support such processes. Right now, it is much easier to buy components anew than to scavenge them from e-waste devices around us, but in relying on doing so, we further perpetuate a making culture that assumes continuous and plentiful supply of materials – an unsustainable approach.

To design for users as recyclers, we proposed an interactive tool that enables electronics designers to explore recycling electronic components during the design process.[13] We accomplish this via suggestions that assist users in choosing recycled components; and maintaining a library of useful data relevant to reuse (e.g., allowing users to find which devices contain which components). Our team went through multiple iterations of designing device prototypes that used mostly recycled components and used learnings from those experiences to guide our tool development as seen in Figure 2.

However, ultimately, we wanted to study users taking on the role of recyclers. To investigate this, we conducted a study where participants used our tool to create an electronic design of their own, but only with components from e-waste devices they had to teardown themselves. Two major findings of ours included how participants felt the experience made recycling e-waste feel possible and made them reflect more deeply on how e-waste was generated. In fact, two participants expressed how they started to look for ways to recycle electronic components immediately after participating in study activities. Our findings showed how people are eager to enter roles like recycler but need the tools and resources to do so. Using the role of recycler to guide our design allowed us to engage with the pain points of recycling and design a software solution to facilitate users becoming recyclers.

EXPANDING USER ROLES

In the previous two examples, we explored the user as caretaker and recycler. Designing interactive technologies with these roles in mind led to explorations that allowed us to think beyond extractive use and instead, build towards more sustainable futures in computing. However, while we explored caretaker and recycler, we see many more "roles" that go beyond the stereotypical role of the "user of a device". Here, we offer some additional user-roles with narratives around what designing for these roles might enable. As organized in Table 1, these other roles include collaborator, partner, adapter, maintainer, archiver, and repairer. Additionally, we see augmenting these roles as beneficial to larger aims in sustainable computing such as increasing device longevity and supporting interactions post-use. While these roles are far from comprehensive, these are meant to provoke new framings of new ways to envision the user-device relationship, especially towards more sustainable computing futures. It is worth noting that some of these roles overlap in some dimensions (maintenance can also be seen as caretaking) but we offer them as distinct to highlight their different dimensions of user interactions.

TABLE 1. Alternative user-roles for sustainable computing.

Category	Role	Description & Relevant Work
for device longevity	Caretaker	cares for device to sustain it[11,12]
	Collaborator	contributes to device functionality[14]
	Partner	invests in long-term relations with device[15,16]
	Adapter	modifies device with changing needs[16,17]
	Maintainer	performs routine work to preserve functionality[18]
for post-use	Recycler	appropriates device to create new forms[13]
	Archiver	preserves and documents devices[19]
	Repairer	fixes devices after breakdown[18,20]

User-roles for device longevity

Within the "user" framing, devices are interacted with through a highly extractive relationship. However, in a more sustainable world, devices should be designed with longevity of use in mind rather than expect that devices will be used up and disposed. Perhaps this could be achieved if our devices were designed with collaborators, partners, adapters, and maintainers in mind instead of just users.

Collaborators are users who contribute something to the technological system for it to work (e.g., harvested energy that powers the device). Thus, interactions are only fruitful when user and device collaborate. Such a user-role requires designs that do not revolve around only the user's needs or in response to the user's demands but requires a more relational exchange. Examples of this entail harvesting energy from user activities (running, walking, biking, sweat) or activity-driven interactions.[14] Envisioning users as collaborators enables reframing technological resources as not abundant and easily replenishable but as allowed by extractive and labor-intensive processes. Thus, designing for collaborators can inspire new ways of interacting with devices and inspire designs that encourage a greater sense of responsibility in device use.

Partners are users that are invested in a longitudinal relationship with their device (spanning many years or, even for the rest of their life). Like collaborators, partners both rely on and support their devices, but living with a device long-term brings in a new set of challenges beyond short term collaborations with devices. Device partners already exist in the form of cyborgs, people with insulin pumps, cochlear implants, smart home inhabitants, and more.[15-16] Such partnerships include challenges like ensuring upgradability or maintainability as well as the dependence on and attachment to such devices for quality of life. Designing for partners requires new methods to sustain these partnerships even when consumer device companies go out of business or replacements are no longer widely available in markets. Exploring alternatives will be essential for ensuring sustainability of both partners.

Adapters are users who hack/mod/remix devices over time. Just as there are abundant strategies to adapt clothing for personal needs or to match current trends (e.g., tailoring, patching, reconstruction, and more), one can imagine similar practices made possible for electronic devices with a foundation of knowledge and best practices developed and widely shared. These adaptive practices can already be seen when interactive devices are modified for people with disabilities (i.e., adaptive tech[17]) or in creative, hacked-together solutions (i.e., reprogramming smart homes[16]). To facilitate users in the roles of adapters, we can envision practices like designing devices with modularity in mind—by designing components meant to be exchangeable or modifiable (e.g., *Framework* laptops)—instead of current usually immutable designs (i.e., single device that is discarded if a new feature is needed).

Maintainers are users who perform work required to ensure devices can continue to operate as expected. While this certainly involves already existing maintenance practices (e.g., updates, cleaning, tightening, organizing), designers should also keep in mind how users & organizations will attempt to maintain devices over the years (e.g., writing drivers for discarded devices to work on modern operating systems). Exploring how we structure our device designs to improve the user's ability to maintain (and thus, sustain) them might enable new approaches for interactivity that foreground maintenance practices rather than relegating them to the background or to obsolescence.[18]

User-roles for devices post-use

While technological innovation has enabled computing to become a huge part of our daily lives, rapid innovation also leaves many technologies in the dust as they become obsolete, broken down, or decayed. The "user" framing can absolve users of any responsibility to such devices, but then who is left to deal with these leftover devices? Instead, what if users were empowered to become responsible for their devices post-use? We present roles that could account for this, such as envisioning users as archivers and repairers of devices even after their intended-use timeframe.

Archivers are users that find ways to preserve and document devices despite rapid technological growth, innovation, and obsolescence (for some devices at a rate of 1-2 years[5]). Whether for historical preservation and learning or to enable more long-term use of devices that have become obsolete in one part of the world (and commonly donated to less wealthy communities for them to "figure out"[6]), archivers and preservers will be essential to ensuring that the path is not only forward (only through new and novel devices) and instead, but we can also find ourselves back to previous versions of devices.[19]

Repairers are users that fix devices upon inevitable break down. While currently, repair is often overlooked by users who find it much easier to buy anew, repair work can significantly reduce our need to consume and dispose of devices. Repair technicians are incredibly knowledgeable and skillful, providing the valuable and essential service of fixing the devices that enable the technological infrastructures of our daily lives.[18] Recently, the idea that the average consumer should also be empowered to become repairers has also gained traction.[20] Often, however, devices are designed to be antagonistic towards the acts of repair (a fact that is most clearly argued by the Right to Repair movement). Making devices amenable to repairers is necessary for both extending the lifetime of device use and reducing the amount of material that becomes e-waste.[20] Facilitating the role of repairer is thus a key site for sustainable computing.

CONCLUSION

The environmental crisis requires us to rethink our relationship to the world which includes how we approach building the future of technology. This is most clear when considering the immense amount of material resources extracted to manufacture and run our technological devices and infrastructure as well as in the tons of e-waste left behind by our perpetuation of rapid technological growth and obsolescence. We argue that our orientation towards user-centered design must change. Instead, device design should encourage users to take on roles that expand beyond extractive use and instead encourage values like care, maintenance, and sustainability. We present two of our projects that go beyond 'user'-centric design and instead, were designed specifically to explore the user in the roles of caretaker and recycler for interactive devices. However, future work should expand beyond these roles too. Thus, we posit additional roles that could be explored to design the next generation of pervasive devices with sustainability in mind. Just as pervasive computing has seen an explosion in the types of devices throughout our worlds and daily lives, pervasive sustainability will require us to envision users that wear a plethora of different hats in interacting with devices. We hope other engineers and designers can similarly find new user-roles to design for in paving the way for more sustainable futures in computing.

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