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Figure 1: We propose ecoEDA, an interactive electronics design tool that enables electronic components to be reused in new projects rather than simply ending up as e-waste. Our tool enables various pathways for electronics designers to prioritize recycling during the design process such as exploring reusable components via suggestions or importing printed circuit board projects into a library of recyclable components. Through use of our tool, components in typical e-waste can be given a second life in new project designs.

ABSTRACT

The amount of e-waste generated by discarding devices is enormous but options for recycling remain limited. However, inside a discarded device (from consumer devices to one's own prototypes), an electronics designer could find dozens to thousands of reusable components, including microcontrollers, sensors, voltage regulators, etc. Despite this, existing electronic design tools assume users

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© 2023 Copyright held by the owner/author(s). Publication rights licensed to ACM. ACM ISBN 979-8-4007-0132-0/23/10...\$15.00 https://doi.org/10.1145/3586183.3606745 will buy all components anew. To tackle this, we propose ecoEDA, an interactive tool that enables electronics designers to explore recycling electronic components during the design process. We accomplish this via (1) creating suggestions to assist users in identifying and designing with recycled components; and (2) maintaining a library of useful data relevant to reuse (e.g., allowing users to find which devices contain which components). Through example use-cases, we demonstrate how our tool can enable various pathways to recycling e-waste. To evaluate it, we conducted a user study where participants used our tool to create an electronic schematic with components from torn-down e-waste devices. We found that participants' designs made with ecoEDA featured an average of 66% of recycled components. Last, we reflect on challenges and opportunities for building software that promotes e-waste reuse.

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CCS CONCEPTS

• Human-centered computing; • Human computer interaction (HCI); • Interactive system and tools;

KEYWORDS

Sustainability, recycling, reuse, electronic design automation (EDA)

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1 INTRODUCTION

As the number of new electronic devices on the market grows, so do the piles of waste from broken or outdated devices. In fact, e-waste or electronic waste is the fastest-growing waste stream in the world [12, 19]. While most users may see their broken or outdated devices as trash, an electronics designer can find dozens to thousands of electronic components in any typical device. Many of these will be well-preserved components, such as sensors, microcontrollers, voltage-regulators, and more; all with the potential to be reused on new prototypes.

Take as an example the popular Roomba, an electronic vacuum cleaner. Our research team found one of these devices in the trash and deconstructed it to illustrate how many electronic components can be found in a common electronic device. Figure 2 depicts how this singular Roomba contains 500+ components, such as capacitors, transistors, diodes, integrated circuits (ICs) including voltage regulators, connectors, buttons, crystal resonators, a Wi-Fi module, and a CPU—most of these in pristine quality (we tested and reused many in new electronic designs for this paper).

Not only is e-waste a major ecological issue but recent chip shortages made sourcing components extremely difficult. The chip shortage driven by the COVID-19 pandemic has significantly stalled electronic designs worldwide [5]. Electronics engineers, makers, and researchers experienced lead times on popular chips increasing so much that they were impractical for use in designs [21]. During this time, some companies and engineers were dumpster-diving for chips in e-waste out of desperation [9]. However, these instances were either centered around a singular component or ad-hoc cases.

The process of reusing components from e-waste involves many non-trivial steps, including: (1) teardown of the e-waste device; (2) component identification, removal & testing; (3) investigating the compatibility of a recycled component as an alternative in the user's design; and (4) altering a circuit's design to integrate the re-used component. Currently, users lack appropriate tools to support these processes of reusing electronic components. Moreover, many of these non-trivial challenges occur during the circuit design phase (e.g., steps 3-4). These remain a challenge because electronics design automation (EDA) software assumes users will buy all components anew from suppliers.

To begin tackling this issue, we propose ecoEDA, an interactive tool that: (1) creates suggestions during design to assist users in sourcing alternative components from discarded devices; and (2) maintains a library of useful data relevant to reusing components hundreds of reusable components



Figure 2: This Roomba was found in the trash but contains hundreds of reusable components on its PCB.

(e.g., allowing users to find which devices contain which components), which users can edit, expand, or even share. We demonstrate the potential of our tool through several use-cases of engineering with recycled components and through a user study evaluating the tool in recycling e-waste during schematic design.

Importantly, all examples in this paper were made with reused electronics. Our sources included devices authors found in trash bins, discarded devices donated from friends or "free/giveaway" forums, and broken devices sold for parts on eBay. We did this to: (1) immerse ourselves in the challenges of recycling electronics; (2) illustrate the potential of our tool in a wide range of sources for scavenging reusable parts, and (3) responsibly engage with this topic by reusing electronics, even during the prototype phase, and not generating unnecessary carbon footprint.

Finally, we note that as a tool that supports component reuse *during* electronics circuit design, ecoEDA is designed for users with electronics design & engineering knowledge, such as engineers, makers, hobbyists, researchers, and others.

2 RELATED WORK

Our work builds on electronic design automation (EDA) tools, electronics prototyping toolkits, and other explorations in recycling electronics. Moreover, our tool's approach is inspired by in-editor recommender. Last, we draw from past work in Sustainable HCI in motivating the goals of this work.

2.1 Electronic Design Automation (EDA) tools

Electronic Design Automation (EDA) tools allow users to interactively design their circuit schematic (using linked symbols to represent components and their connections); and translate this schematic into a physical board design (printed circuit board, PCB). EDAs also typically generate a bill of materials (BOM) with all components the user added to their circuit—this list is used to buy these components. This process is so common that the generated BOMs can often even be automatically ordered from component suppliers within the EDA software. Inherently, most EDAs are structured with the assumption that components will be bought anew rather than sourced from alternative sources. These tools vary in complexity depending on the target user, from industry-level (to implement most mainstream devices) to novice-friendly (for learning/teaching). For example, fritzing [20] and Tinkercad circuits [35] are tools for smaller productions, breadboard-prototyping, and classrooms, whereas Eagle [14], Altium [1], and KiCad [31] are used by both professionals and hobbyists alike. We chose to develop with KiCad due to its popularity as an EDA among many professionals and as open source and free software for designing electronic circuits. While we chose to implement our work with KiCad, our work can also be adapted/extended by other researchers (or users) for other EDA tools.

2.2 In-editor recommender systems

Apart from electronic design automation tools, our work is also inspired by prior work on recommender systems. While most research on recommender systems personalizes recommendations for users based on consumer patterns or health interventions [7, 55], our approach is more related to recommender systems inside domainspecific tools. In recent years, with the proliferation of personal fabrication, 3D editors have been embedded with functionality that recommends operations to users *while* 3D modeling. For instance, *ShapeStructuralizer* [9] suggests alternative shape designs while *TrussFab* [34] assists with structurally-sound forms. Similarly, we created ecoEDA to provide users with eco-alternatives *while* they are designing electronic circuits.

2.3 Electronics Prototyping

While personal fabrication has much research on assisting users directly inside their editor, electronics has been different. The emphasis on interactive tools and toolkits has been in supporting the earlier phases of the design (breadboards, modular toolkits, etc.). For instance, to assist users in building simple circuits, AutoFritz creates suggestions for extending or completing a circuit as users add components to a virtual breadboard [40]. Similarly, to make physical electronics prototyping more accessible, .NET gadgeteer developed a system for rapidly building devices with modules and standardized connectors [59]. To reduce the need to manufacture PCBs during early prototyping, Circuit Stickers presents a fabrication method of adhering electronic components to connective substrates [25]. While these works assist users with rapid prototyping in the early phases, they do not support the engineering of circuit schematics to be printed as circuit boards (PCB), which is where users engage with EDA software to crystalize their designs in a PCB. Recent work by Lin et al. has explored how EDA tools could be reimagined to explore design processes based on abstraction, interactive coding, and hardware descriptive languages [37-39]. These showcase how EDAs emphasize and obfuscate aspects of electronics design and introducing new tools can allow for more accessibility. We are similarly inspired by these works in exploring how EDAs could prioritize reuse.

2.4 Practices in reusing, remixing, and repairing electronics

Engineers have previously reused components for various reasons, including minimizing their device's ecological impact, their own curiosity, technical explorations, and even component shortages. Our work is similarly inspired by existing processes and aims to better support them.

Previous work in waste management has also explored what types of components can be reused among common e-waste and how to test for a part's reusability [12]. Other work has explored building open-source hardware tools to test and reprogram common chips, enabling them for reuse in new designs [49].

Technical curiosity has also led many to build electronic devices from repurposed parts, create teardown videos, or reverse engineer devices [11, 15, 17, 63, 65]—often shared on communities such as *Hackaday* [23] or *Instructables* [64]. In fact, recent work has documented various 'folk strategies' of experts engaged with unmaking e-waste [29]. Additionally, component shortages forced individuals and companies to consider reusing components while creating their PCBs [10]. In communities where parts are hard to come by and lack local or domestic supply chains, reuse and remixing are key parts of electronics design and repair [36].

Last, a significant driving force behind component reuse is device repairability [26, 27, 53]. Recently, individuals and many governments recognized the importance of repairing devices to minimize e-waste. In fact, some governments have taken steps in this direction by requiring the standardization of components [16] or requiring companies to make repair parts accessible [47]. Moreover, several organizations like iFixIt provide guides to empower users to repair [47]. While reusing, remixing, and repair of electronics has been accomplished in the past by individual users, to the best of our knowledge, there has not been any research building interactive tools to support this process.

2.5 Towards more sustainable HCI

The principles behind our work are influenced by Sustainable Interaction Design, in which Blevis highlighted two goals: linking invention and disposal and promoting renewal and reuse [6]. These are central to our work, and we explore them in electronics design a domain central to HCI and computing but often overlooked for sustainability.

In previous work on difficulties of electronics reuse, Maestri and Wakkary surveyed how people approached repairing everyday objects and found that "[T]he simple nature of mechanical objects enable repair, though the presence of electronics and computational mechanisms in digital objects add further complexity that make adaptations and resourcefulness difficult" [41]. This is echoed in *Practices in the creative reuse of e-waste*, where authors determined that a majority of reuse focuses "solely on the exterior properties of e-waste", or in other words, the mechanical enclosures of devices [33]. Other researchers have tried to mitigate this; for instance, by facilitating workshops that provide a space for tearing down devices and learning about their inner workings [3, 45, 46, 61].

Recent work also looked at approximating the environmental costs of prototyping in the HCI community and even discusses reuse of electronic components as a strategy for more sustainable prototyping [57]. In *Making with limits: Towards salvage fabrica-tion*, authors highlight how making with salvaged materials allows for unique engagements with resource scarcity, sustainability, and

disposal [13]. Other research has focused on developing more sustainable processes during the prototyping process such as repurposing existing materials [24, 43, 62], using biodegradable materials [2, 58], and integrating unmaking in their designs [8, 54, 56]. With ecoEDA, we strive to contribute to these approaches by building tool support for remixing and reuse of electronics components that would otherwise become e-waste.

3 ECOEDA: RECYCLING COMPONENTS DURING DESIGN

ecoEDA is an interactive tool that assists users in reusing electronic components from discarded devices. While there are many processes involved in reusing e-waste components (teardown of devices, identifying components, testing components, and adapting designs for reuse), we focus in on building with the tools commonly involved during the design process (i.e., while using EDAs), enabling support in information management and circuit design iterations. As such, ecoEDA integrates with KiCad to facilitate reusing electronic components during schematic design or even PCB design.

To assist users in recycling components, our tool revolves around two main elements: (1) ecoEDA suggestions, which provides suggestions to the user during their schematic design, recommending alternative yet compatible reusable electronic components rather than purchasing components anew and (2) ecoEDA library, a library management system designed specifically to organize and distribute information that is critical for reuse but typically missing from electronic design software (especially, compatibility of a component with other components, source device, PCB labels, etc.). Within our tool, these elements offer support for different design strategies such as a design first, recycle second approach (starting from an existing design and finding potential recycled components that could be swapped in) or a recycled-component inspired design approach (designing around found components). As such, our features were designed to emphasize checking compatibility of components, evaluating trade-offs, and discovering unique or relevant components in the library.

4 WALKTHROUGH

To showcase our tool, we describe a walkthrough of a user creating an electronic conference badge that includes a microcontroller, screen, speaker, and vibromotor. In this walkthrough and throughout the paper, our tools gather information from our ecoEDA library, a list of components found inside discarded devices. To make this walkthrough succinct, this user has already torn down the discarded devices for the components in their ecoEDA-library; thus, in this walkthrough, we focus on use of the tool with an existing library (see <u>Implementation</u> on how users add parts to the library or share libraries with other users). This walkthrough also focuses on a user developing a design from scratch rather than iterating on an existing schematic design (also supported by our tool).

Our user starts creating the schematic using KiCad. First, they add the central piece of their electronic badge—the PCD8544 display, a popular LCD display due to its low-cost and existing libraries for many microcontrollers.

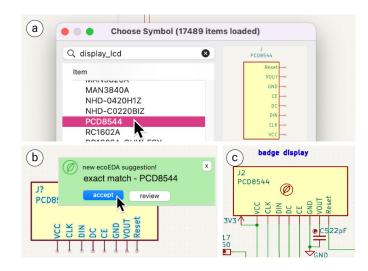


Figure 3: (a) In KiCad, ecoEDA can find (b) exact matches for components; (c) reused components have a leaf symbol.

Replacing a component with an <u>exact match</u>. Figure 3 illustrates how our tool detects a component in the library that is an exact match to the PCD8544 display. In response, our tool triggers a pop-up notification inside KiCad to inform the user that their desired component exists within the ecoEDA library. Our user accepts the replacement and instead of ordering a new PCD8544, they can now source it from a broken Nokia 5110 phone. As such, the PCD8544 component is now shown on KiCad's schematic view annotated with a O (leaf) symbol that denotes a recycled part.

Reusing via a drop-in replacement. Now, the user adds the second most important component-an ATMEGA328P-A microcontroller (a widely known chip that made the Arduino popular). In response, as depicted in Figure 4 (a), our tool announces an available drop-in replacement. Drop-in replacements are trusted components that can be swapped for the original and maintain the same functionality, footprint (physical size on the PCB), and pinout (layout of physical pins). These components may have different specifications but functionally are similar. Often this exists for popular chips with variants (ATMEGA328 and 48 have different memory specs as seen in descriptions in Figure 4). ecoEDA suggests the ATMEGA48PA from the user's broken FG05 signal generator. The user compares the two components via the tool, decides the swap is also appropriate for their design, and accepts this recommendation. Then, ecoEDA automatically edits the schematic to replace the ATMEGA328P-A with the recycled ATMEGA48PA.

Suggesting reusing a part with a different footprint. Now that a microcontroller is chosen, the user creates a voltage supply for the ATMEGA48PA which requires 5V. They choose the popular 7805 voltage regulator. Our tool informs the user of an exact match with different footprint. As shown in Figure 4(b), the user clicks "review" and ecoEDA displays a GUI that allows the user to compare the original footprint (TO-220) side by side with recycled one (TO-92) from their broken Febreze Scent Stories (a fragrance diffuser). The user reviews, accepts, and ecoEDA swaps in the recycled part.

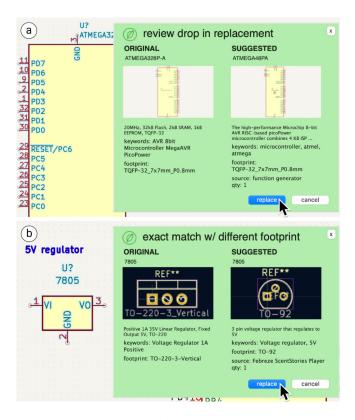


Figure 4: ecoEDA suggests (a) drop-in replacements (uses the same footprint) and (b) exact matches with different footprints.

Ranked suggestions with ecoEDA. Now, our user needs a resonator for their microcontroller, which they achieve by adding a 20 MHz Crystal. As depicted in Figure 5 (a), our tool notifies the user that ranked suggestions are available. The user chooses to review, and our tool displays a list. We use our ranking system to offer the most likely matches (using string distance, weighted keywords, and component type heuristics - described in detail in *Implementation*).

Moreover, as shown in Figure 5 (b), our tool allows the user to filter suggestions by value or footprint. In this case, a 16MHz crystal was ranked first, followed by other crystals that scored lower in similarity. Using our tool, the user compares parameters, pinouts, footprints, and even device sources and quantities side by side. Finally, the user chooses to replace the 20MHz crystal with the recycled 16MHz crystal from their broken Roomba (as it falls within the required value range for their microcontroller). The user continues to add the required passive components around the microcontroller as well as a vibration motor and a buzzer—note that they can continue to replace these via ecoEDA.

Smarter replacements using <u>subcircuits</u>. Now, to interface the ATMEGA48PA with the LCD display, the user adds a 74AHCT125 (a quad-level shifter that converts 5V signals to 3V3). As depicted in Figure 6, our tool informs the user that a subcircuit replacement is available. The user reviews and finds an alternative way to realize the 74AHCT125's functionality by reusing four NPN UIST '23, October 29-November 01, 2023, San Francisco, CA, USA

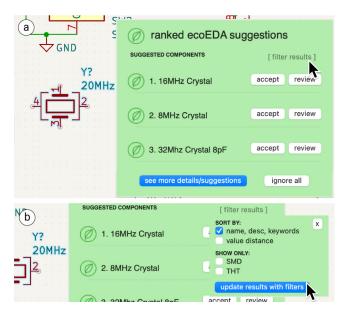


Figure 5: (a) Ranked suggestions based on name, keywords, and descriptions. (b) Filtering suggestions by footprint or value.

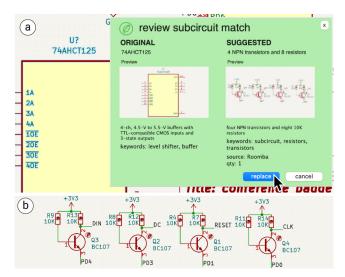


Figure 6: (a) User adds a 7AHCT125 level shifter and our tool suggests replacing it with (b) a *subcircuit* of reused parts.

transistors and eight 10K resistors from their broken Roomba. The user accepts this, and our tool alters their schematic in response.

<u>Bill of teardowns to assist with assembly</u>. A common feature of EDAs is a *bill of materials* (list of components to order). As shown in Figure 7, our tool outputs a *bill of teardowns*. The user can click through this guide to see components in their project grouped by their sources (the discarded devices where the components can be found). It contains helpful information for retrieving these components from their source device such as their PCB designators (label on PCB next to component) and URLs to teardowns.

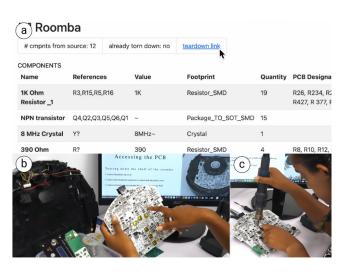


Figure 7: (a) ecoEDA groups reused components by source and organizes information (e.g., teardown links.). (b) A user viewing a teardown guide for the Roomba (linked from our UI) and desoldering a needed component.

Circular reuse by <u>importing old projects</u>. Later, if the user decides to scrap this electronic conference badge, they can reuse its components on new projects. ecoEDA allows users to reimport their schematics into its library, providing a new life for components that would have become e-waste. This enables any previously designed electronics schematic to be imported into our ecoEDA library even if it was not designed with our tool (e.g., Eagle or Altium designs can be converted to KiCad via a feature already present in KiCad). In addition to recycling old projects, this also enables the import of open-source hardware schematics into the library in case the user has old/unwanted open-source devices around.

Engaging with <u>statistics of reuse</u> over time. Last, as shown in Figure 8, we want to facilitate a long-term engagement with reuse. To do so, we show statistics about project reuse, the number of components available for reuse, and how much of each project reused components. In addition to encouraging users to continue practicing reuse, we also see this as helping facilitate a more creative engagement with a user's process in designing with electronics allowing them to consider how they can better incorporate reuse into their practice.

5 CONTRIBUTION, BENEFITS, AND LIMITATIONS

Our key contribution is that we propose and implement an interactive tool designed to support the process of *reusing* components from discarded devices during design. In addition, we demonstrated the use of our tool through examples and evaluated it through a user study. Our approach provides three key benefits: **(1) Component recall and management:** one of the difficulties in reusing components from discarded devices is recalling all of the components that can be found in each device—our tool assists with this by recalling components automatically—e.g., in a Roomba, one might immediately recall it has motors and sensors, as these are directly Jasmine Lu et al.



Figure 8: In (a) statistics of user's reuse; (b) the final conference badge and all the devices that components were sourced from.

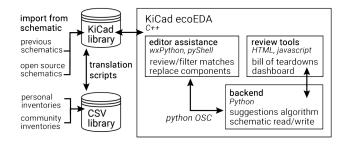
tied to its functionality, but it would be *unthinkable* to recall values for 300+ resistors, 150+ capacitors, 40+ transistors, and 20+ ICs. (2) **Component level reuse:** our tool enables remixes originating from the component-level rather than the device-level. In doing so we dramatically multiply the number of ways a device could be used in new projects beyond its intended functionality (e.g., a signal generator provides the microcontroller for an electronic conference badge). (3) **Sharing across users:** ultimately, the library that each user maintains when they tear down discarded devices and map what can be found inside is the key piece of knowledge that can accelerate other users' designs—our tool enables users to share and exchange libraries of the components.

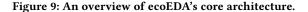
While we see our approach as the first step towards building tools for component reuse, it is not without limitations: (1) it depends on users' ability to identify and test components from devices (while efforts exist to use computer vision to automatically extract components, these are emergent systems [42, 52]); (2) some devices might be designed to discourage being taken apart; (3) not all components are equally straightforward to reuse and test, as some age differently and expire faster (e.g., capacitors and batteries); and finally, (4) recycling is always more time consuming than not-recycling (this applies to recycling non-electronic materials too); however, this is only a short-term perspective, since recycling trades off time with ecological savings, which is a principle our system hopes to inspire in users. Notably, our work focuses on assisting reuse during the

design process (via the editor) but much work remains to support a larger ecosystem of electronics reuse.

6 IMPLEMENTATION

ecoEDA is implemented in Python, a modified KiCad C++ build, and HTML/Javascript. All code, libraries and installation instructions will be made open-source¹. We show our tool's architecture in Figure 9.





6.1 ecoEDA in KiCad editor

We modified KiCad to enable a more seamless integration of ecoEDA in the editor by allowing a single button click to enable suggestions during design. However, our tool can also be used with standard, unmodified distributions of KiCad via additional installation/setup (we used this version in our user study for distribution simplicity). In-editor assistance. Our in-editor support is implemented in Python and makes use of KiCad's Pyshell. While a user is editing their schematic in KiCad, our scripts monitor their file for new component additions and search through the ecoEDA library to identify suggestions. Notifications of these suggestions appear within the KiCad editor and users can review these suggestions in a more detailed view or accept them immediately. If accepted, our backend scripts remove the original and replace it with the accepted ecoEDA component at the original component's location (so that users do not lose state in design), writing to the schematic file and updating the editor. Users are now fully able to build upon and manipulate the newly added ecoEDA component.

Suggestions. ecoEDA uses its library's information to offer appropriate suggestions either as specific typed suggestions (exact match, drop-in, footprint, subcircuit) or, by default, as a ranked list of alternatives. We rank components by scoring the similarity of text fields (name, keywords, and description) and assigning weights corresponding to field importance. We score component names based on Levenshtein edit distance and longest common subsequence to create matches. While both are common algorithms, they are especially relevant to naming conventions of electronic components. For example, the linear regulator in our *Walkthrough* (7805) can be found as WS7805, L7805, 78L05, depending on variations in manufacturer, footprint, packaging, etc. For components where values have high relevance (i.e., passive types), values are also factored into their ranking score. Additionally, ranked suggestions can be further filtered by value or if surface-mounted or

¹https://lab.plopes.org/#ecoEDA

through-hole. Value-based filtering is especially useful for reusing passive components as designers may need components within a range or can combine components for a specific value. Last, suggestions prioritize exact match, then drop-in, exact match different footprint, subcircuit, and ranked suggestion in that order. Users always have the option to get ranked suggestions if the original suggestion doesn't fit.

6.2 ecoEDA library

We designed our ecoEDA library to be initially created as a Comma Separated Values (CSV) file to allow for interoperability so that others can extend it and share it. A component is defined via its name, component type, footprint, value, source device, quantity, keywords, description, and optionally, PCB designator, URL to teardown, datasheet, and drop-in or subcircuit equivalency.

KiCad library support. To allow users to make use of the library during design, our tool converts the CSV to KiCad's internal representation (*.kicad_sym*) that can be used as a standard component library. Modifications can be made within KiCad like other libraries or can be made to the CSV. Additionally, when creating an ecoEDA KiCad library, additional information is used from the original KiCad symbol, drawing from their default libraries (like when components extend from other components) to create tags like drop in or different footprint type suggestions.

Sharing knowledge across users. Our tools enable multiple users to collaborate on inventorying components from devices. The CSV format allows the library to be hosted in cloud-based services (i.e., *Google Sheets*), enabling collaborative editing and sharing, pooling information on devices to scavenge from. Hosting the library also allows the latest changes to be pulled when the user accesses it.

Importing, writing to, and parsing schematics. Our tool can import existing schematics to their ecoEDA library (to encourage reuse of the user's own projects or open-source hardware) and parse through KiCad schematics (to generate suggestions and statistics). These build on KiCad's *kicad-library-utils* [30] and community-made scripts [32].

7 REUSE CASES WITH ECOEDA

While our walkthrough depicted a step-by-step example of ecoEDA used during the design of a new electronic device, we now present additional example use cases of ecoEDA.

7.1 PCB rapid prototyping with reused components

In this example, we showcase how our tool enables rapid prototyping with PCBs. This might sound paradoxical to an electronics engineer since making a PCB typically involves two waiting periods: (1) manufacturing the PCBs and (2) acquiring components from a supplier. With the emergence of low-cost CNCs, the first step's wait has been reduced, as personal fabrication machines now include PCB printing (e.g., the *Voltera* is a printer that fabricates PCBs using a low-resistance conductive trace in a matter of minutes). However, the second step often involves significant time waiting for a supplier to fill out an order. We show an alternative workflow in Figure 10.

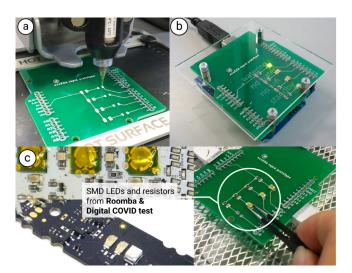


Figure 10: In (a) users use a Voltera and to (b) rapidly prototype PCBs with (c) recycled components.

With ecoEDA, users rapidly populate PCBs with reused components. Figure 10 depicts an Arduino-shield with LEDs to indicate their watering system status. These parts were all sourced from a Roomba and Ellume Digital COVID Test. This PCB was created in 41 minutes (32 minutes to print via Voltera, 6 minutes to desolder components, and 3 minutes to solder)—faster than a trip to an electronics store and much faster than waiting for parts to be shipped.

7.2 Reuse with popular frameworks (e.g., Arduino)

Our tool can also integrate well when designing with popular toolkits. We illustrate this through an input device created using ecoEDA. These projects became widespread among makers due to the popularity of toolkits such as Arduino. Figure 11 depicts a Photoshop controller that allows users to toggle quickly between fill/brushes using button presses and choose brush-size using a rotary encoder. The complete project, except the Arduino, is recycled: buttons and encoder sourced from a mouse and resistors from a fragrance diffuser.

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Figure 11: (a) Circuit schematic for (b) input controller; (c) the device and component sources.

7.3 Component reuse without PCB manufacturing

While our previous examples depict devices created on PCBs, ecoEDA is not limited to PCBs. We show an example of an *energy-harvesting charger* soldered on a protoboard. This device allows the user to generate energy by rolling the wheel of the motor. In turn, the power generated is rectified and filtered through capacitors, then regulated down to 5V, which then can be used to charge a phone through USB. This entire project is recycled—voltage regulating circuit with USB-A connector from a car charger, DC wheel motor from a Roomba, and capacitors and diodes from a power supply PCB as shown in Figure 12.

8 USER STUDY: ECOEDA DURING SCHEMATIC DESIGN

To evaluate the design of our tool and explore user needs for electronic component reuse during schematic design, we conducted a user study where participants tore down e-waste devices, cataloged components into a shared library, and then, used our tool to construct electronic schematic designs. Whereas our walkthrough and use-cases demonstrate fully implemented prototypes, here we focus on specific needs during schematic design (rather than implementation). As our tool is a prototype and introduces new workflows to traditional KiCad schematic design, our study focuses on participants' feedback on the challenges and opportunities of designing with recycled components in-editor rather than quantitative metrics (task completion time, accuracy, etc.). This study was considered exempt of ethical concerns by our Institutional Review Board (IRB21-1200).

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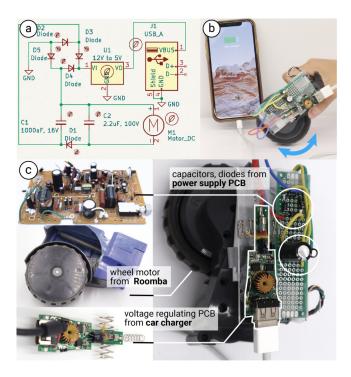


Figure 12: (a) Circuit for energy harvesting; (b) device in action, charging an iPhone; (c) overview of device and sources.

8.1 Participants

We recruited 12 participants from an electronics engineering course at our institution. The course consisted of a mixture of graduate and senior undergraduate students, mostly from computer science and engineering backgrounds. The course covered PCB manufacturing, electronics design, and KiCad.

Our participants included 6 women (one identifying as transgender), 4 men, 1 non-binary individual, and 1 chose not to disclose their gender identity. Participants were an average age of 23.45 (SD=2.81). Participants were compensated with a \$50 gift certificate for their time.

8.2 Structure

Our study was conducted over the course of a week and followed up with individual interviews. The study consisted of two sessions: (1) an e-waste device teardown session and (2) ecoEDA installation and tool walkthrough.

1. Teardown session. Participants were given one of the following discarded devices: vacuum cleaner, video-conferencing camera, PC motherboard, laptop, Xbox Kinect, Bluetooth speaker, AM/FM radio, USB car-charger, toy drone, gamepad, remote-controlled toy, and cable modem. We aimed to supply a variety of device types that allowed participants to explore different issues in recycling e-waste. After the teardown session, participants were given three days to complete a component inventory of their torn-down device. They submitted a CSV inventory with information such as component name, component type, SMD vs. THT, keywords, description, quantity, PCB designator, source device, and KiCad equivalent symbol and footprint. These inventories were merged in a shared library of 192 unique components that was distributed to participants. After this, participants completed a questionnaire about their teardown experience and inventorying process.

2. ecoEDA use. Participants were shown how to install the tool on their own KiCad (version 7). Then, participants were asked to create a new schematic design using the tool where they could engage with reusing components. They were also asked to submit a copy of their *ecoEDA dashboard* and *Bill of Teardowns* alongside their final design. After completing the activity, participants were interviewed about their design, workflow, challenges encountered and how our tool altered their thinking about e-waste reuse. For the sake of time, our study focused on use of the tool *during* schematic design and did not ask participants to implement their final designs.

8.3 Results

Overall participants final designs included an average of 66.37% recycled components (SD=17.01%)—their designs averaged 28.5 components (SD=12.64) total with 18.8 recycled components (SD= 9.39). Resistors and capacitors were the most recycled components with buttons and LEDs closely following. Other recycled components included microcontrollers, crystals, sensors, USB connectors, transistors, and op-amps. Components in designs originated from an average of 6.67 source devices (SD=2.71). The participants' designed projects included a programmable keypad, a dimmable night-light, a wearable featuring an accelerometer, and ATTINY85-based miniature violin.

Questionnaires and interviews were analyzed via open coding by the first author. One participant (P12) was not able to complete the interview on their tool use. We produced 162 codes in total and analyzed how often participants converged on these codes. Based on this we developed themes that we felt encompassed sentiments and experiences expressed by participants. We organized our findings into four themes: (1) design workflows, (2) reuse tradeoffs, (3) desired features, and (4) reflections on e-waste reuse.

Theme 1: design workflows. Participants had diverse approaches to creating a schematic with reused components. While seven participants started from an idea/design and used the tool to find swaps, four participants drew inspiration from the components in the library to develop their design. Similarly, diverse workflows were used alongside the tool. P1, P2, P3, P8, P5, P10, P11 started from an idea and built from the ground up. P7, P9, P4, P6 used the ecoEDA on their own previously engineered designs and explored swapping in recycled components. P1, P2 used a combination of the suggestion feature or directly accessing the ecoEDA library through KiCad's component browser. P4, P5, P9, P10 sometimes used the suggestion feature but mostly relied on manual use of the library. P3, P7, P8 only added components manually via the library. P6, P11 only used the suggestion feature (never directly accessing the library).

Six participants noted the KiCad integrated ecoEDA library as the most helpful component of the tool. This was usually because it allowed participants to access components in a familiar way. Participants also described the automated suggestions as useful for building a mental map of components in the library (P1), accessing the most relevant components (P2, P6, P11), a "design first, recycle second" approach (P3), comparing differences across suggested components (P2), reducing the need of scanning through a full inventory list every time (P6), and allowing an alternative pathway to finding recyclable components (P5). Other participants also noted the recycling-specific information within the library (P10, P11) and Bill of Teardowns and the dashboard (P6, P9) as helpful.

Theme 2: reuse tradeoffs. Participants described various approaches they used when trying to reuse components. These included incorporating similar but different parts they would not use by default (P4, P7), using components of a slightly different value if some tolerance was allowed (P1, P10, P11), or connecting reused resistors/capacitors in series/parallel to achieve a target value (P3, P7). On the other hand, participants also discussed various reasons for opting not to recycle components. For example, P1 was designing an analog synthesizer where the resistors needed precise values to generate certain pitches. Similarly, P7 expressed that they preferred to design with their go-to voltage regulator component. P1, P5, P8 also expressed interest in reusing certain components but found them too complex to use. However, P1 also noted that they appreciated the fact that in reusing components from manufactured devices, they were selecting from a "curated" list of components used by professionals rather than looking through the hundreds of thousands on supplier websites (i.e., Mouser, DigiKey). Last, P1, P6, and P10 also stated aspects that might make them more hesitant to reuse. P1 stated how normally, they would take stock quantity into consideration in case they needed to order replacements. With reuse, it may not be possible to reorder these components so backup options are limited. P6 noticed how this process was different from how they usually approach designing as they might need to adapt the circuit to the components on hand, requiring additional work. Finally, P10 added that their comfort with reuse might depend on the state of the source device or how it was damaged.

Participants also noted several challenges during the teardown and inventorying process that might prevent them from pursuing reuse. Challenges during teardown included difficult to open enclosures, proprietary or hidden screws (P1, P2, P10), desoldering challenges (P2, P3, P4, P9, P11), and damaging components during teardown (P6). Notably, this was very device dependent as some participants described each others challenges as the easiest part of the teardown and P7 even described the whole teardown as easy. Challenges during inventorying included locating relevant datasheets or symbol/footprint libraries (P1, P3, P6, P12), the amount of time required to inventory all components of a device (P2, P11), sheer amount of components (P7), measuring component values (P5, P11), identifying components based off limited identifiers (P4, P5, P8, P11, P12), and the process being tedious (P8, P9).

Theme 3: desired features. We asked participants what additional features they wanted in future tools for reuse. Five participants expressed wanting more direct control of suggestions (i.e., selecting components and right-clicking to see suggestions). P1, P8 wanted more diverse component configurations in suggestions (i.e, including modular break-out boards). Participants also suggested alternative flows for accessing ecoEDA library information such as grouping components of similar type together (P5, P9), pulling information from datasheets and presenting in-editor (P5), notifications when exceeding component quantity (P4, P10), and reviewing all suggestions together at the end of design (P6, P10). Five participants speculated on what tools could reduce challenges of the teardown and inventorying processes including computer-vision aided inventorying (P1), open-sourced schematics (P6, P7), and automated teardown machines (P4, P7). Importantly, nine participants stated they could envision using ecoEDA in their own practice. Of the other three, P1, P8 stated they would use it depending on how streamlined inventorying could become (e.g., manual entry vs. getting libraries from others), while P10 stated they would use it with a "review all suggestions at the end" feature.

Theme 4: reflections on e-waste reuse. All but one participant (P5) said that they see themselves reusing electronics in the future, and P5 explained that it was primarily because they do not usually design electronic devices but this process made them more confident they could reuse electronics (also expressed by P2, P3, P6, P11). Notably, P6, P10 shared that between completion of the design activity and interview, they had already recycled components (outside of our study). When asked how our tool affected their thoughts on sustainability in electronics, most participants expressed that it made recycling electronics feel more possible. P1, P3, P11 reflected on how broken devices were often thought of as broken in their entirety but components could be salvaged. Participants also expressed frustration over wastefulness in electronics prototyping (P1, P2, P9), lack of repairability in devices (P2, P8, P10), desire for changes in electronics workflows or designs (P6, P7), and needing more investment in this area (P4, P11).

When asked what they learned about electronics design by using this tool, participants noted many outcomes. First, six participants described it helpful to see electronics design in context and to see how other professionals designed their PCBs. Similarly, seven participants described the process as "demystifying" devices. Many noted that they learned of interesting design patterns from both the teardown and the design process. In three cases (P1, P6, P7), participants were inspired to adopt specific approaches to increase reusability of their future electronics projects. Last, participants primarily commented on how the process inspired creativity in two ways: (1) by introducing the constraint of working with components already on hand (P2, P4, P6, P9, P10), and (2) by broadening the horizons of what could be made by seeing existing designs (P3, P5, P8, P11).

8.4 Discussion of study findings

We highlight critical findings of our study and address some limitations. We summarize our critical findings as (1) reusing electronics made possible, (2) reframing e-waste, and (3) using different workflows for reuse.

Reusing electronics made possible. Overall, we believe the strongest takeaway from our study is that providing tools that support reuse during design allowed users to feel that reusing electronics is possible. As shown by the two participants that immediately began participating in component reuse after teardown and design activities, participants felt empowered to incorporate reuse in their electronics prototyping practices and even discussed how to change their practices to make their prototypes more reusable in the future.

Reframing e-waste. Undergoing this exercise in tearing devices apart, logging components, and designing with components from e-waste enabled participants to engage with common electronics in a different way. As such, participants connected their experiences with the broader electronics industries, reflecting on how consumer electronics manufacturing was more wasteful than it needed to be or how electronics manufacturing *could be* more sustainable. Additionally, sustainability concerns became a central concern during electronics design with the tool.

Using different workflows for reuse. In terms of tool design, participants seemed to prefer workflows with the tool that mirrored traditional KiCad electronic design workflows (which likely felt more familiar to use) but valued the ecoEDA suggestions UI for discovery, comparison, and curation purposes. As our tool was a prototype, it was less polished and contained bugs that might have made features more difficult to use; however, we believe user's feedback and desire to use a tool like this in their practice offers insights into how to better design such tools to support electronic component reuse during design. For instance, participants often noted how component reuse required additional constraints and considerations that induced a less linear design process, likely requiring multiple iterations and adjustments particular to reuse. Additionally, participants approached the design process with diverse strategies, signaling how tools for reuse require flexibility.

Study limitations. As with any study, our design included intentional tradeoffs between participants' time (this study took one week) and diversity of electronic designs. As such, we recommend that results are interpreted with these limitations in mind. We opted for a more open-ended design rather than a predefined task to see how participants respond to the frictions of freely designing with reused components. As such, each participant's experience was different since they constructed different schematics. Doing so allowed participants to design with components they had seen in their teardowns, grounding the study in the process of reusing actual components. Moreover, we did not have participants go through the step of actualizing their designs by soldering, as we focused on our tool's assistance during the design process. Similarly, actualizing their schematic via PCB design was not a requirement, so considerations of component footprint were less important for participants. Also, testing components prior to reuse was not the focus of the study and remains an open challenge, which we discuss later. Last, our participants were all recruited from an engineering course, and many were relatively new to PCB design. More experienced engineers would likely have different insights and considerations for reusing components. Despite these limitations, we believe this study provides a first step into understanding that an EDA that assists with reuse can promote recycling and engage users with the ecological footprint of electronics design.

9 REFLECTIONS ON SUPPORTING ELECTRONICS REUSE

As the first work to explore how electronic design tools can be designed to facilitate reuse, we build off our own explorations and our user study to discuss our reflections and learnings on supporting e-waste reuse. We present three reflections: (1) considerations for reusability in electronics, (2) supporting component recycling in design, and (3) moving towards an electronics recycling paradigm.

9.1 Reflection 1: considerations for reusability in electronics

While the reuse of electronic components (as with recycling any material) tends to present more difficulty than buying anew, we also found that component reuse is more accessible than one might realize. To give a better sense of this, we synthesized some considerations to ground our work in how practically components can be reused.

Reuse by source device. As shown in Figure 13, different devices require different considerations for reuse. If a source device is functional, it presents fewer challenges to reuse. Its functional state allows users to test components without desoldering. Conversely, a broken device presents one further challenge: avoiding damaged components. Identifying causes for a damaged device depends on one's skill. The type of source device can also affect its components' reusability. Mainstream devices from the last decade might have obfuscated components to prevent reuse; however, these have often been already torn down by others and have guides online. Recent devices are excellent sources for popular microcontrollers, wireless modules, and USB connectors. Another common but controversial type is single-use or disposable devices such as emergency USB phone chargers, disposable vapes, and more recently, single-use digital health tests (pregnancy tests or digital COVID19 tests). Even antiquated devices (e.g., engineered last century) are viable sources for components, though they will often have more THT components than SMD components.

If an engineer has a device schematic on hand (in the case of open-source devices or their own prototypes), devices become much easier to recycle. As of this date, the *Open Source Hardware Foundation* has certified 1800+ devices with this status [50], while there are arguably many more. This reduces the difficulty in inventorying components and allows for the benefits of circular reuse during prototyping. We see these types of devices as the strongest candidate for component reuse.

Reuse by component type. Common components (resistors, capacitors, diodes, voltage regulators, LEDs, buttons, switches, etc.) are usually somewhat standardized across devices. Resistors are essential to nearly any type of circuit, which leads to significant quantities of them found (e.g., 300+ on the Roomba) and are often well-labeled with codes. Components that tend to be used in power-regulating circuits (diodes, regulators, capacitors), may require additional tests and can be riskier to reuse. Capacitors and batteries are also ubiquitous in electronic devices but require careful considerations in reuse [44]. Electrolytic capacitors and batteries (e.g., LiPos) have a limited lifespan (e.g., 500-800 charge/discharge cycles depending on the use conditions [51]). While engineers have several ways to test capacitors and batteries for leaks or test their discharge curves [7], these are riskier for reuse. Conversely, we found ceramic capacitors to be easier to reuse, especially those used in low-voltage settings. Sensors, actuators, and microcontrollers are often the most rewarding components to reuse but can present some additional steps (e.g., reprogramming or protocols). Analog sensors (bump sensor, light sensor, etc.) can often be tested simply



Figure 13: Exemplary source devices and some components inside them: (a) hot glue gun, (b) Amazon Dash button, (c) HP Computer Motherboard, (d) Leapfrog Toy Laptop, (e) Ellume Digital COVID test, (f) vacuum-tube TV, (g) Creality 3D Printer Driver, and (h) Furby interactive toy.

with a multimeter or simple test circuits. Digital sensors, on the other hand, need to communicate through a microcontroller (via I2C or SPI), requiring additional skill. Actuators (e.g., motors) can be found in many devices; while a DC motor can be tested in devices easily, more advanced actuators (e.g., LRAs) require specialized driving circuitry. Finally, microcontrollers are embedded in most all modern electronic devices and are often the most sought-out components, but they can also present unique reuse challenges. For one, companies often intentionally obfuscate markings or chip names to discourage this (often for security reasons) [48]. However, many also contain programming pins that can be used to test and determine if they are reprogrammable. In other cases, manufacturers might have security locks, so that users need to erase prior memory to upload firmware. Reusing a microcontroller requires the highest level of skill among the components we reused. **Reuse by** *footprint*. In terms of component footprint, SMD vs. THT components require additional considerations. We found that a hot-air gun and tweezers removed most SMD components in a matter of seconds. However, certain packages like QFN or BGA will be more difficult to desolder as they do not present exposed leads. Techniques like using a hotplate to heat up the PCB can be used in these cases. However, sometimes these components might also require additional processes before reuse (like reballing for BGAs). Through-hole components are also possible to desolder but require one extra consideration: the legs on a THT component are typically clipped after soldering, which means that their leg length cannot be adjusted. This creates less flexibility but can be circumvented by using a stricter (less tolerant) footprint size in the user's new PCB.

Ecological impact of component reuse. The simple choice to reuse over purchasing anew means at least one less component in a landfill. However, component reuse is not all equal in terms of ecological footprint. Many factors affect the environmental cost of manufacturing components (mining of raw materials, supply chain logistics, emissions in manufacturing, etc.) and much research has been done to quantify the ecological footprint of this [18, 22, 60]. As this research suggests, the more complex the manufacturing process of a component, the more ecological footprint it carries. For example, microcontrollers tend to be the ideal candidates for ecological-inspired reuse. Other ICs, such as logic gates or levelshifters also have complex processes, and in many cases, these can be replicated with other components (e.g., resistors, transistors)as demonstrated in our "subcircuit" feature in the Walkthrough. One of the biggest potential benefits of prioritizing component reuse over buying anew is that there are significant savings on the shipping and transportation costs of individual components. Even for passive components like resistors and capacitors that are less costly to manufacture and purchase due to their ubiquity, users can remove the environmental costs of shipping and packaging by not buying them anew for new projects and instead, looking to devices around them (which likely already have these components in similar values).

9.2 Reflection 2: supporting component recycling in design

Current tools in electronic design are reflective of common practices in electronics design and manufacturing across industries and hobbyists alike. For the most part, they assume components can be sourced and bought anew and don't incorporate additional constraints for practices in reuse. In our work, we explored how EDAs could be designed with an alternative workflow to facilitate recycling components and built features around common reuse swap types. Our design revolved around three main ideas: (1) component recall and management, (2) component-level reuse, and (3) sharing knowledge across users. Additionally, our approach intervenes during the design process depending on the user's choices and ultimately relies on the user's expertise to make critical decisions about their design. However, tools that support a variety of workflows for electronic recycling are needed to allow diverse audiences to feel confident in incorporating recycling during design.

We also see our tool as primarily beneficial for the prototyping process, where engineers can take on some risk of failure and are open to exploration. Again, there are many tradeoffs to reusing components and engineers that are bound by time constraints or need polished designs are not ideal candidates for recycling. Additionally, buying new components (often for very cheap) remains a much more straightforward process than recycling. However, we also believe that more investment in tools to support this process would make others feel more comfortable with integrating reuse in their practice (even in small ways). Many participants in our study explained that they had never really considered recycling components from electronics before. We believe this speaks to the lack of tools and engagement in this area and want to emphasize that creating tools with a focus on recycling components allows engineers to consider reuse as a possibility.

9.3 Reflection 3: towards an electronics recycling paradigm

Our work focuses on supporting electronics reuse during the design process in an EDA, but there are many other opportunities for facilitating other e-waste recycling processes. Other opportunities include building out systems that improve taking apart and identifying components in devices, testing components for reusability, and enabling pathways for novices outside the EDA. These opportunities are non-trivial as it involves synthesizing of large amounts of information (common electronics design patterns, millions of different IC types, millions of consumer devices, etc.). However, there are also clear gains from an investment in developing an electronics component recycling paradigm. The primary benefit is sustainability and reducing the carbon footprint of electronics design, but we also see benefits in engineering education and promoting values of right-to-repair/open-source hardware (as shown by study participant reflections). Our approach of creative component reuse generally exists in much smaller scales compared to the volume of electronics industry production. Often, recycling by raw material extraction is offered as a means of managing the massive amounts of generated e-waste, but these processes have been shown to also produce mass quantities of waste and pollutants [4, 28]. Thus, scholars have often emphasized the importance of reuse practices over recycling via material extraction [36]. Additionally, electronics recycling must contend with the ever-changing consumer market landscape, further complicated by new standards, gray markets, trends, and more. While our approach definitely will not solve the issue of e-waste alone, we hope that our work can foster the building of new tools and systems across varying scales to support reframing e-waste as potentially useful material and move us toward a more sustainable electronics recycling paradigm.

10 CONCLUSION

We implemented the first interactive EDA tool that enables users to reuse the electronic components sourced from their discarded devices. Rather than allow these devices to end up as a pile of e-waste, our tool gives some components a second life in new projects. Users interact with our tool directly via KiCad during their schematic design process and receive real-time suggestions of alternative components. In a user study, we found that participants were able to find recycled alternatives for most of the components in their designs. Our participants also revealed that the process enabled them to approach prototyping with sustainability in mind. Finally, we synthesized our reflections on designing this tool and building devices from reused components in hopes that others can build on our work to imagine new pathways for creative e-waste reuse and new tools to support this process. We see ecoEDA as a starting point to support reusing e-waste. This closer engagement with the "insides" of our devices also makes us more responsible and knowledgeable about our e-waste—shifting us from just users or consumers to *recyclers*. We hope our research can inspire discussions about designing interactions with our devices even after they become broken or obsolete.

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