A Tale of Two Mice: Sustainable Electronics Design and Prototyping

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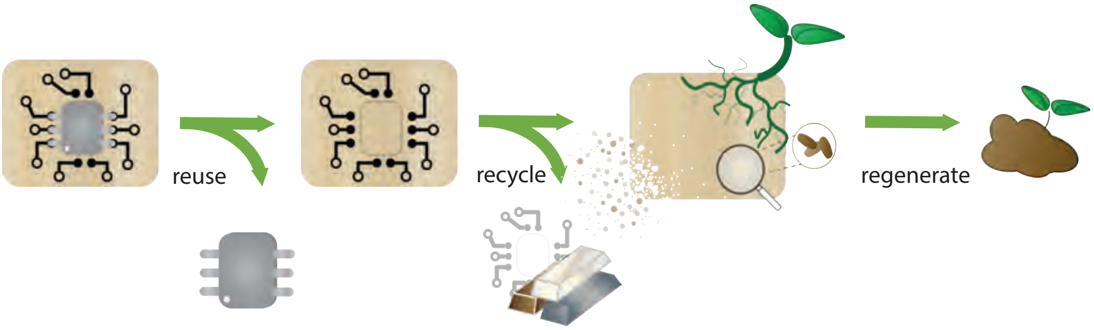

Figure 1: A vision for sustainable electronics. The figure illustrates a vision for a fully circular production cycle in which electronics can be disassembled for component reuse, metal recycling, and/or substrate regeneration through the natural biological cycle. Using this sustainability vision, we develop and demonstrate a working computer mouse prototype built with a biodegradable printed circuit board. Demo video: https://homes.cs.washington.edu/~vsiyer/biomouse.html

ABSTRACT

Electronics have become integral to all aspects of life and form the physical foundation of computing; however electronic waste (e-waste) is among the fastest growing global waste streams and poses significant health and climate implications. We present a design guideline for sustainable electronics and use it to build a functional computer mouse with a biodegradable printed circuit board and case. We develop an end-to-end digital fabrication process using accessible maker tools to build circuits on biodegradable substrates that reduce embodied carbon and toxic waste. Our biodegradable circuit board sends data over USB at 800 kbps and generates 12 MHz signals without distortion. Our circuit board dissolves in water (in 5.5 min at 100 °C, 5 hrs at 20 °C) and we successfully recover and reuse two types of chips after dissolving. We also present an environmental assessment showing our design reduces the environmental carbon impact (kg CO2e) by 60.2% compared to a traditional mouse.

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CCS CONCEPTS

• **Hardware** → **Printed circuit boards**; **Circuit substrates**; • **Human-centered computing** → **Pointing devices**; • **Computer systems organization** → *Embedded hardware.*

KEYWORDS

biodegradable electronics, sustainability, sustainable HCI (SHCI) hardware, maker, digital fabrication, life cycle assessment, design for disassembly

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1 INTRODUCTION

Electronics play a critical role in everything from cars and smartphones to medical devices, appliances and so much more. With rapid advancements and deployments of new technologies, devices using older generation hardware quickly become obsolete and discarded for their latest counterparts. For example, the average smartphone is used an estimated 2-3 years before being upgraded [29]. In 2019 this rapid consumption cycle for electronics generated approximately 53.6 million metric tons (Mt) of e-waste, and this figure is expected to grow rapidly to over 74 (Mt) annually by 2030, making e-waste the fastest growing waste stream at 2 Mt per year [9]. At the same time, recycling rates of e-waste are growing by only 0.4 Mt per year.

Electronics are some of the most complex waste streams due to the large variety of components and their constituent materials. This includes metals like lead used to reduce the melting point of solder or gold and copper for conductive traces, semiconductor materials such as gallium arsenide used for high performance transistors, thermoset and thermoplastic resins, and various specialty chemicals such as flame retardants. While these materials have desirable properties for their respective applications, many of them are also highly toxic which have significant adverse implications for human health and environmental justice. The complex nature and hazardous materials imposes high costs for recycling, which has led many wealthier, more developed nations to send their e-waste abroad [30].

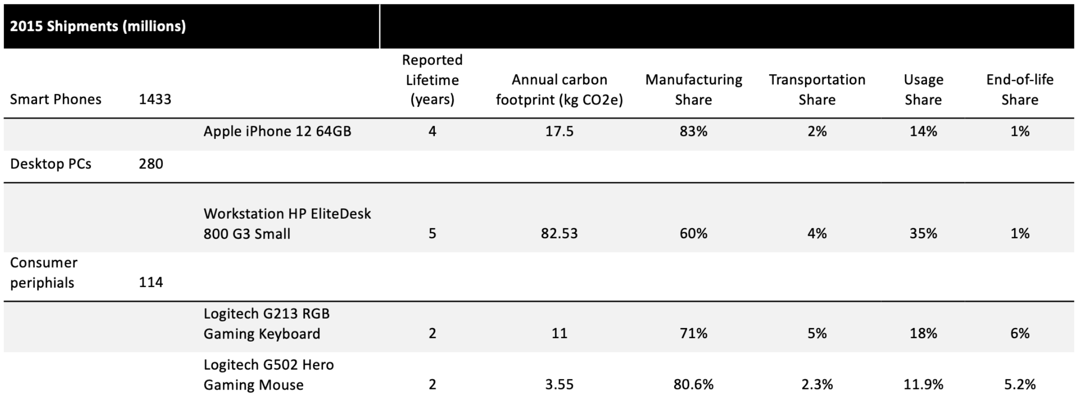
In this work we explore an alternative, sustainable vision for the future of electronics prototyping and manufacturing illustrated in Fig. 1. Specifically, can we create a fully circular production cycle, in which electronics can be recycled, reused, or regenerated through the natural biological cycle? We emphasize that this vision of designing real devices that incorporate biodegradable materials is not an abstract future that relies on technologies that have yet to be invented. In this work we demonstrate it is possible to build an end-to-end functional computer mouse that incorporates *existing biodegradable materials and fabrication techniques*. We choose a mouse as a case study and show that we can immediately reduce embodied the carbon footprint and mitigate the harms of e-waste through design. We approach the problem of e-waste through the lens of sustainable HCI (SCHI) [2, 17, 22] and present four guiding principles for designing and prototyping electronics which we outline below:

- **Reduce silicon.** We seek to reduce the number of silicon chips and can achieve this by selecting highly integrated systems on chip (SoCs) which require few external components. Silicon is the primary semiconductor material that makes up the majority of electronic chips. We observe that a significant portion of a consumer device's total carbon footprint comes from manufacturing (Fig 2). For example, it is estimated that over 80% or more of carbon footprint of many electronics comes from their manufacturing, of which production of ICs dominate [14, 37]. This is due to the extremely high energy costs of semiconductor manufacturing equipment (e.g. 2000 °F furnaces, specialized lithography tools, etc).
- **Improve circularity.** We observe that many circuits use general purpose components such as microcontrollers which can be easily adapted and reused for a variety of designs. We demonstrate that these components can be removed from the printed circuit board (PCB) during disposal and successfully recycled or reused, extending the lifetime and reducing environment impacts of the components.
- **Incorporate biodegradability.** We design the remainder of the device including the PCB and plastic enclosure using environmentally friendly, biodegradable materials. For all other materials that are difficult to recycle or reuse in a technical circular framework, we advocate the introduction of a biological cycle where materials returned to the biosphere and can be naturally regenerated [10].
- **Evaluate environmental impacts.** We estimate the carbon footprint of our prototypes using LCA – a methodology to estimate and assess environmental impacts of a device. LCA results tend to be qualitative in practice due to lack of accurate data sources and assumptions in the system boundary, but LCA provides approximations used for steering decisions towards lower environmental impact options.

This work makes the following specific contributions to SHCI in the emerging area of sustainable fabrication: First, we propose a sustainable design framework described above. Second, we utilize commercially available tools to create circuits on *biodegradable* materials. Our workflow consists of a series of digital fabrication methods such as laser cutting and conductive ink printing optimized for rapid prototyping that will enable the research community to easily adopt this workflow. Third, we demonstrate a working prototype of a consumer input device that incorporates a biodegradable printed circuit board and case. We evaluate our biodegradable circuit by demonstrating its traces can transfer data over USB at rates as high as 800 kbps and evaluate its thermal performance. Fourth, we evaluate an end-of-life disposal procedure showing the circuit board can dissolve in 5.5 min in boiling water or within a few hours at room temperature. Fifth, we demonstrate the feasibility of recovering and reusing two different ICs and show that this process does not impact their performance. Sixth, we evaluate the carbon footprint of our mouse design, measured in kilograms of CO2 equivalent (kg CO2e), and compare it to a common consumer mouse made with conventional materials to demonstrate our design could reduce the embodied environmental impacts by 60.2% of CO2e.

2 RELATED WORK

Improving the sustainability of electronics has been explored in the past decade by academics, entrepreneurs, and hobbyists who have sought to integrate novel materiality and fabrication with environmental social awareness; however much of this work has focused on developing novel materials for biodegradable plastics



2015 Shipments (millions)								
Smart Phones	1433		Reported Lifetime (years)	Annual carbon footprint (kg CO2e)	Manufacturing Share	Transportation Share	Usage Share	End-of-life Share
		Apple iPhone 12 64GB	4	17.5	83%	2%	14%	1%
Desktop PCs	280							
		Workstation HP EliteDesk 800 G3 Small	5	82.53	60%	4%	35%	1%
Consumer periphials	114							
		Logitech G213 RGB Gaming Keyboard	2	11	71%	5%	18%	6%
		Logitech G502 Hero Gaming Mouse	2	3.55	80.6%	2.3%	11.9%	5.2%

Figure 2: Volume of common electronic devices shipped in 2015. Examples of smartphones, Desktop PCs and peripherals with their reported lifetimes and carbon footprint demonstrate the scale of global e-waste. Contribution of each of the life cycle phases (manufacture, transport, use, and end-of-life) for specific models are shown. [20, 26]

and packaging, substrates for printed circuit boards (PCBs), and transient electronics. Our work builds upon this foundation, and focuses on the next step of creating a design framework, fabrication process, and building real-world systems.

Eco-friendly materials have been explored to reduce single-use plastics. For example startups such as Wave (using wheat straw), Pelacase (using flax straw and compostable plastic blend), and MMore (using pressed coffee grinds) have built biodegradable phone cases. These works however do not include circuits.

Alternatives to fiberglass PCBs have also been explored. The simplest were made from either printing or drawing metal inks on paper, cardboard, and other materials to create single [18, 35] and multi-layer [25] flexible circuits and have been used extensively in the HCI community for rapid prototyping [5, 12, 21, 28, 33, 34]. While paper is biodegradable, it is not mechanically rigid, which is necessary for many circuit boards. Additionally, it is not flame resistant and cannot tolerate common assembly procedures such as soldering. Alternative materials made from banana [13] and cellulose fibers [3] have also been reported in the literature, but have not been incorporated into functional prototypes.

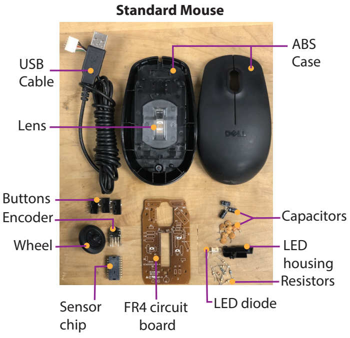
Beyond the substrates themselves, research into transient electronics is an active field of research [18, 41]. Transient electronics are designed with similar functions as integrated circuits but have the additional capability to completely vanish in their environment through active control or passive mechanisms. In addition to the promise of reduced e-waste, transient electronics have the potential to reduce environmental impacts by utilizing simpler manufacturing processes than conventional ICs [16]. While these works are important fundamental contributions towards the goal of fully biodegradable electronics without silicon, their capabilities are far from the specs needed for use in even the simplest consumer electronic devices. For example, some biodegradable transistors can degrade quickly when removed from a sealed nitrogen glovebox [4].

A recent and growing body of work in the HCI community has also begun to explore this domain of sustainable fabrication and novel ideas such as un-making [19, 23, 36, 39, 40]. We seek to complement prior efforts demonstrating laser patterning of carbon traces on wood [19] as well as mycelium breadboards and accessories [39, 40], by developing methods to incorporate fine pitch solderable electronic parts used extensively in consumer electronics to enable more complex circuits. We synthesize this rich background of work into a functional mouse prototype. We further highlight through our LCA that by simply reducing the number of silicon components, making components of the device like the enclosure and PCB biodegradable, and by reusing components, we can significantly reduce e-waste impacts *immediately*.

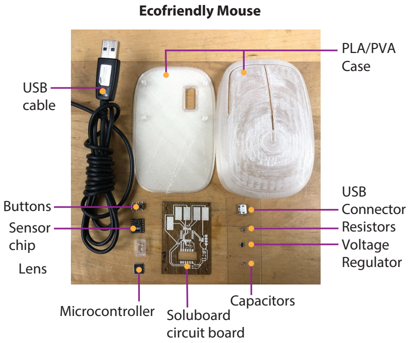
3 SUSTAINABLE MOUSE DESIGN

To design our more sustainable mouse, we first deconstruct a conventional optical computer mouse (Dell 468-7409 model) in Fig 3. The core components include a light-emitting diode (LED), buttons, capacitors, resistors, encoder, wheel, and the core sensing element that detects the direction of motion. The LED provides a light source, and the transparent plastic lens assembly includes a structure to direct the light downward onto the surface the mouse is moving on and a lens to focus it onto the sensor. The remaining components include the PCB made of standard FR4, which holds the components and the physical enclosure made of ABS plastic. Fig 3 shows each of the components which we use later on in our cradle-to-gate LCA.

After identifying the core requirements of a mouse, we proceed to follow the design principles outlined above. First, we seek to design a minimalistic circuit with as few components as possible. To do this, we analyze the size of the sensor element itself and how many external passive components such as resistors and capacitors it requires. In contrast, Fig 3 shows our design. We selected a small mouse sensor with an integrated LED (PAW3805EK-CJV1). The movement data are then sampled by a microcontroller (ATSAMD21E18) and sent via USB to the computer to move the cursor. We fabricate our prototype by first cutting the desired PCB shape out of a flax fiber-based composite (Jiva Soluboard) using a laser cutter. We show that wood substrates could also be used (see Appendix A), and this method could be extended to other dielectric materials made of cellulose or natural fibers. We then pattern the circuit traces using a conductive ink printer (Voltera V-One), and hand solder the components. We then 3D print a plastic enclosure



Item	Quantity	Mass (g)
Mouse case	1	50.51
Mouse wheel	1	3.56
Lens	1	2.36
Cable	1	28.98
Circuit board	1	5.52
Buttons	3	0.547
Sensor/processor	1	1.08
LED Diode	1	0.234
Capacitors	11	1.276
Resistors	10	0.7745



Item	Quantity	Mass (g)
Mouse case	1	26.46
Lens	1	0.284
Cable	1	22
USB Connector	1	0.228
Circuit board	1	3.88
Buttons	2	0.264
Microcontroller	1	0.143
Sensor	1	0.309
Capacitors	5	0.016
Resistors	22	0.011

Figure 3: Mouse component. A breakdown of two mice highlighting components in (left) commercial wired mouse and (right) our redesigned eco-friendly mouse consisting of minimal electronics, a biodegradable PCB, and a compostable case.

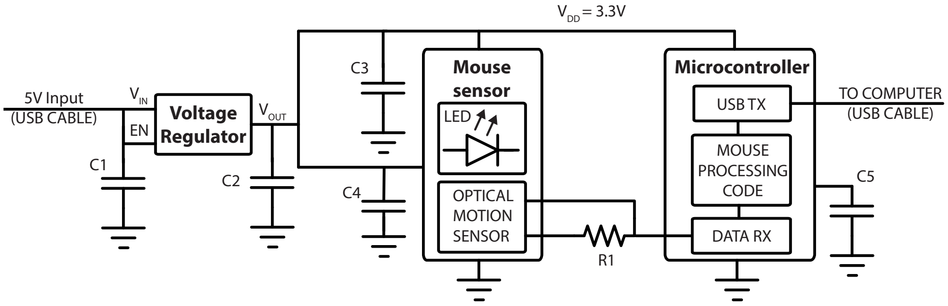


Figure 4: Mouse circuit diagram. High level circuit diagram showing the components used in our mouse design. The circuit primarily consists of the sensor chip which integrates an LED, the microcontroller which receives the data and sends it to a computer, and small surface mount passive components such as resistors and capacitors.

for the mouse using polyvinyl alcohol (PVA). This material can dissolve in water for disposal, leaving only the remaining components that can then be re-used. The same printing process can be applied to PLA filaments that meet commercial composting standards such as EN 13432 or ASTM D6400 [7, 8, 31, 32]. These materials would also provide greater durability to sweat and water for extended use. We also experiment with novel algal biomass composite printing filaments [11, 24]. Details of the fabrication method are explained in supplementary material (see Appendix A).

4 EVALUATION

We evaluate our design by measuring circuit performance and comparing it with a conventional FR4 design. Next, we evaluate the disposal process and demonstrate dissolving a circuit in water and recovering the components. We then evaluate the performance of a recycled component. Additionally, we compare the environmental impact of a conventional computer mouse design and compare it to our prototype.

4.1 Circuit performance

We first compare the power consumption of the soluboard circuit to the FR4 version by programing each circuit with the same code and connecting a multimeter (Fluke 287) to the power input to measure the current. Next, we apply a constant 5 V input from a benchtop power supply (BK Precision 1670A) and measure the average current over 1 min. Current measurements on both circuits are within 1 mA, showing that trace resistance does not significantly impact power consumption. This difference may be more noticeable for higher power levels, but the lower conductivity of the Voltera circuits is negligible for many low power embedded devices.

In addition to power consumption, we are also interested in the thermal properties of the circuit. We program each circuit to run a benchmark that performs a series of operations like floating point multiplication and divisions to simulate a computational load and generate excess heat. We run the benchmark code continuously for 3 min and capture an image with a thermal camera (FLIR One) shown in Fig 5. The images show negligible difference between the two circuits in thermal performance, demonstrating that our sustainable alternative will not cause excessive heat buildup. We also record the performance data from these tests and observe that the operations take the same time on each chip. Fig 5 shows the results, which shows equivalent performance for each chip and no variance across multiple trials. We note that the lack of variance makes sense considering the tests execute an operation that takes the same number of clock cycles on each chip, and the cycle jitter of the oscillator is less than a microsecond. These timing specs are sufficient for many low frequency microcontroller operations.

We perform multiple experiments to explore the limitations that the traces' material properties may introduce. First, we perform a USB speed test. This code sends test data with a length of 6 kB and records the time required for the transfer. We run this test for 100 iterations (total 600 kB data transferred) on both our FR4 and soluboard circuits, as well as a commercially available development board with the same IC. Fig 6 shows the results. We find that all

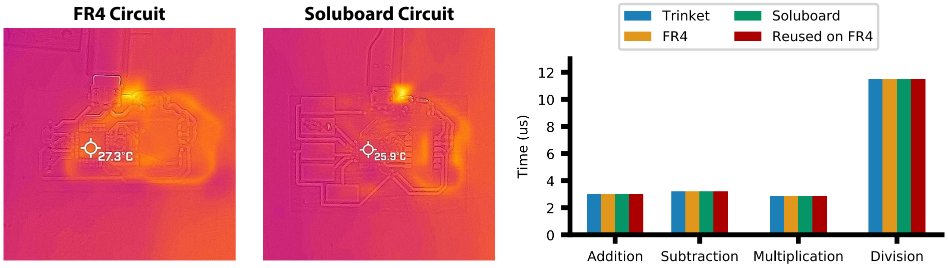


Figure 5: Thermal and Computing Performance. Images from an IR camera show the temperature of an equivalent mouse circuit on FR4 (left) and Soluboard (right) while running a performance benchmark. Benchmark results (right) demonstrate that the chips are not damaged during the fabrication process and the processors function the same. Performance of the same IC on the Adafruit Trinket development board is shown as a reference.

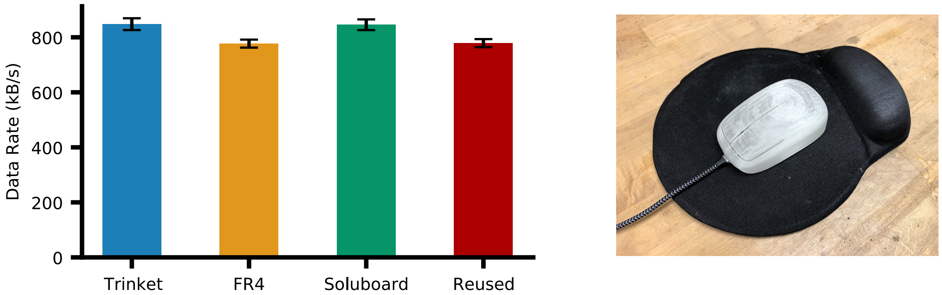


Figure 6: Communication speed benchmark. Result of USB communication speed test for each prototype including a reused microcontroller and voltage regulator and reference comparison of the Adafruit Trinket development board. A finished mouse prototype including the case to house the circuit is also shown (right)

three circuits achieve similar data rates and observe minimal errors at even the highest data rates. These findings are consistent with prior work which has demonstrated this conductive paste material can be used for signals with frequencies up to 2.4 GHz [6, 15].

In addition to these benchmarks we implement code to read data from the optical mouse sensor. We connect our mouse to a laptop computer with a standard USB cable and show it is natively recognized and able to move a cursor as seen in our demonstration video: https://homes.cs.washington.edu/~vsiyer/biomouse.html

4.2 Disposal

We evaluate the disposal of our Soluboard PCBs and PVA case by dissolving them in water. While dissolving PVA 3D printer filament is well documented by manufacturers, there is little data available on the time and heat required to dissolve Soluboard. We perform a series of experiments to determine these requirements. We place a 200 mL beaker filled with 150 mL of water on a hot plate stirrer (Vevor SH-2) and measure the temperature with a thermometer (Thermco Accusafe). We set the stirrer to a low setting (roughly 100 RPM). We then heat the water to various temperatures and record the time it takes for the Soluboard to dissolve. We consider the Soluboard dissolved when it decomposes into a loose bundle of fibers no longer resembling the original rectangle shape. We perform 3 trials each for 2 different sizes of boards (1×1 cm and 3×1.5 cm). For each trial, we replace the water to prevent it from saturating with the water soluble adhesive in the Soluboard. Fig 7 shows these results. We observe a nonlinear decrease in the time required to dissolve the PCB versus temperature. We also observe higher variance in the room temperature case and that surprisingly the smaller samples take longer to dissolve completely. Fiber layers in the smaller samples begin to delaminate at approximately the same rate, but a thin layer retains its original square shape for longer. This may be because the longer fibers are pulled apart more easily by the stirring of the liquid than the smaller samples. We note that alternative case materials (e.g. certified compostable PLA) will not degrade in water but could instead be disposed of in an industrial composting process.

4.3 Component reuse

We also evaluate the feasibility of reusing a component after this disposal process. First, we place a fully populated circuit board in a water bath at 100 °C as shown in Fig 8 and allow the PCB to decompose into fibers and individual ICs. Next, we drain the water and extract the ICs. Considering many chips are sensitive to moisture, we perform a baking process to thoroughly dry them and prevent failures. Specifically, we place our chips in a glass petri dish inside a laboratory oven at 90 °C for 18 hrs. We choose these times conservatively based on recommendations for baking components in industry and note that a shorter time may suffice. After baking, we solder the reused voltage regulator and microcontroller onto a new PCB. We run the same performance benchmarks and as shown in Fig 5 and Fig 6, and we observe no changes in performance.

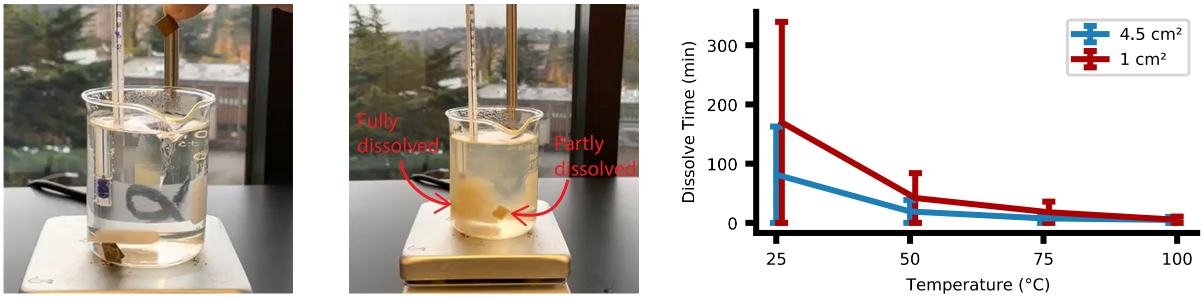


Figure 7: Dissolving Time. At end-of-life soluboard can be dissolved in water. The beginning and partial dissolution are shown (left and center). (Right) The average time required to dissolve soluboard samples of two sizes at different temperatures. Error bars represent ±σ

Figure 8: Component Reuse. Fully populated circuit and PVA mouse case being dissolved in hot water (left). The fibers and components can be recovered after dissolving (center). A recovered chip after baking in an oven to remove moisture is shown (right). This chip and a voltage regulator were successfully reused.

4.4 Carbon footprint of mouse design

We evaluated both mice design using the LCA software GaBi to measure the global warming potential using TRACI 2.1, excluding biogenic carbon in our calculation [1]. We defined our system boundary to include the silicon components, PCB substrate, and plastic case to produce our functional unit (one mouse). We assumed that the USB cable, transport of all components, and the energy to assemble both mice were equal and excluded it in our study. For silicon components already in the GaBi database, we chose appropriate package models for the respective mice components. Plastics in both mice were included based on the type and weight of plastic and the average energy required for injection molding. Both the production of SoluBoard and FR4 PCB substrate are modeled in GaBi based on material, transport, and energy inputs provided by Jiva [27].

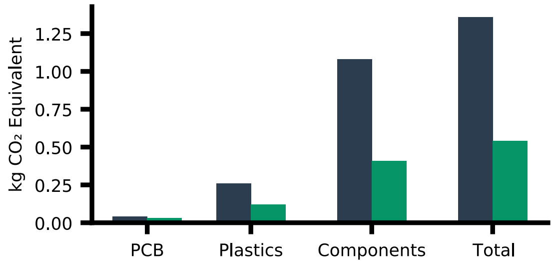
Our preliminary results (Fig 9) suggest that our design can educe the embodied carbon associated with a mouse significantly. Across the three categories PCB, plastics, and components, we see that the silicon components have the most significant carbon impact, followed distantly by plastics and PCB. Reducing the number of components in our mouse has the largest effect on our carbon footprint, reducing CO2e by 60.2% in a mouse! While the PCB and plastics contribution to the carbon footprint of the device is small compared to that of the components, switching from a FR4 substrate to a flax-based substrate could provide a 50% reduction in CO2e from the printed circuit board and similarly over 50% for plastics. The advantage of using a biodegradable substrate and compostable plastics is primarily in reducing the e-waste of the device. Furthermore, a biodegradable substrate enables easy reclamation and reuse of components, avoiding further carbon emissions from producing virgin components.

5 DISCUSSION

We discuss limitations of our approach and highlight directions for future work below. Our current fabrication process using the flax-based Soluboard material is slower and lower volume than typical PCB production processes. This could be scaled up by using techniques like screen printing to pattern larger panels or by switching to a conventional subtractive process. Additionally our process is currently limited to single layer PCBs. This is sufficient for many simple designs, but future work could investigate reducing the substrate thickness and laminating multiple layers together similar to the approach used for FR4 boards. Additionally, conductive paste based through hole plating solutions could be explored to enable electrical connections between the layers.

We prototype our designs by hand soldering components, however larger scale production typically involves reflow soldering in which the PCB and components are placed in an oven. We find that the polymer in Soluboard degrades at temperatures (180-200 °C) required for soldering. Alternative methods to circumvent the issue could be use of a lower temperature solder or conductive epoxy or to use emerging RF based heating methods that can precisely melt the solder/cure an epoxy without overheating the PCB [38].

In this work, we show proof-of-concept feasibility results for component reuse; however, several issues currently limit the scalability of this approach. Many disposal processes for biodegradable materials such as composting or dissolving in water as we show involve high humidity. We find that baking the specific components used in our design allowed us to reuse them without issue, however the effects of this process on yields for large scale production and effects on more moisture sensitive components should be investigated. Additionally, while the flax-based Soluboard dissolves well in water, we find components can become entangled in the fibers.



kg CO_2 Equivalent				
Design	**PCB**	**Plastics**	**Components**	**Total**
⬛ Commercial	0.02	0.26	1.08	1.36
🟩 Ecofriendly	0.01	0.12	0.41	0.54

Figure 9: Global warming potential of mouse designs. Results of a cradle-to-gate LCA assessment of carbon footprint of our redesigned sustainable mouse compared to a conventional mouse.

This was particularly an issue when the PVA case was dissolved in the same water bath, as the PVA would act as an adhesive causing the fibers to bundle together and coat the components. This was also most noticeable for components with leads extending out from the package that the fibers could become tangled in. Future work could reduce this issue by both using a separate water bath and using lead-less components.

Our environmental impact assessment focused specifically on carbon emissions which is directly related to climate change. Other environmental impact categories such as blue water consumption, land usage, eutrophication, and human toxicity could be analyzed to understand additional trade offs between the two mice design. Additionally, we could extend our full system boundary to include the full cradle-to-grave environmental impacts.

6 CONCLUSION

E-waste is a growing problem in an increasingly digital world. Our goal is to show how we can begin leveraging existing technologies to immediately start reducing e-waste and carbon generated annually by incorporating environmental sustainability into existing design frameworks. We outline a set of guiding principles for designing sustainable electronic devices which works toward a vision in which no component or part is discarded: *reduce silicon*, *improve circularity*, *incorporate biodegradability*, and *evaluate environmental impacts*. We demonstrate as a first step, that it is possible to design a fully functional mouse prototype that mitigates the embodied carbon footprint and the amount of persistent, non-biodegradable waste of a mouse at end-of-life. We show that our mouse can be easily disassembled in hot water to retrieve the microcontroller and perform initial validation that it can be reused without any damage. Our work illustrates that concrete, immediate steps can be taken to improve the sustainability of electronic devices. We hope that by adopting these design techniques and significantly expanding research in this area we can begin moving closer to the vision of a circular production cycle in which electronics can be recycled and reused, or regenerated through the natural biological cycle.

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A FABRICATION

In this section we describe our fabrication process for our sustainable mouse design in detail. We develop our process using digital fabrication techniques optimized for rapid prototyping. While this particular process is designed for low volume research prototyping, we will also comment on how these steps can be adapted to large scale manufacturing methods.

A.1 Substrate materials

The first step in fabricating our mouse is to select a substrate material for our PCB. The requirements for the substrate are that it should be mechanically stable enough to mount our components on, nonconductive, able to withstand heat for soldering, and sustainable. One option is to use wood. Plywood is available in thin sheets and has the benefit of already being mass produced at scale. While these properties are attractive, typical plywood is primarily made of naturally derived wood is not biodegradable as the adhesives used to bind the layers of wood together contain formaldehyde. Additionally plywood is not fire resistant, which is a common requirement for PCBs. In addition to plywood we also explore the use of Soluboard, a novel composite material produced by the startup Jiva Materials. Soluboard is composed of natural, sustainably sourced flax fibers bound together using a water soluble polymer adhesive and halogen-free flame retardant. Soluboard is designed to delaminate and decompose into fibers when immersed in water, allowing the plant based fibers to be composted and the remaining water is compatible with domestic waste water treatment systems. In the following section we outline our fabrication process for producing functional circuits on both plywood and soluboard.

A.2 Circuit fabrication

We begin by cutting the physical shape of our substrate material such as soluboard or plywood using a laser cutter. Specifically, we use a 40 W desktop laser cutter (Glowforge Basic, 50% power, speed setting 245, 6-9 passes). We observe these cut parameters are similar to those used for cutting balsa wood. The material cuts cleanly without significant deformation, burning or production of hazardous fumes. The heat affected zone of the laser does cause some singeing at the edges and immediately after cutting the PVA used to bind the flax fibers together may be sticky to the touch due to heating of the adhesive.

Next we pattern the substrate with conductive traces using an additive manufacturing process to produce a circuit. Specifically we use the Voltera V-One PCB printer to deposit a conductive silver ink material. To do this we use the following specific steps and settings. We begin by designing a circuit using standard PCB design software (e.g. KiCad, Eagle) and upload the design files into the Voltera software. We note that because our current process only supports a single layer we use 0 Ω resistors to cross over traces instead of vias. Next we follow the Voltera instructions for aligning the holes and probing the height of the board. We probed the boards with a $\approx$ 5 mm pitch. Boards with a height deviation of less than 0.08mm (sometimes up to 0.1mm) produced the best results. Next we followed the Voltera instructions for calibration to set the appropriate ink pressure and nozzle height. These parameters are important to achieve good adherance to the substrate as well as continuous traces similar to the parameters that can be adjusted on a 3D printer. After performing calibration, we wipe the bulk of the calibration pattern off with a dry kimwipe. We then remove the remaining residue with a kim wipe damped with Acetone. We note that Acetone can be used to wipe the surface clean without damaging it but extended exposure can begin to soften the polymer. After completing the calibration steps, we follow Voltera instruction for printing. We use the Voltera supplied conductive ink 2 (NiftyNaga). When not in use, we store the ink in a standard refrigerator. Prior to printing, we remove the ink from the fridge and allow it to warm to room temperature for >15 min. We note that print height and ink pressure may need to be manually adjusted during printing to assure even deposition.

After the printing process is completed we evaluate the results and reprint broken traces. We note that for plyood we reprint the circuit a second time as some of the ink is absorbed into the wood. We observe on both materials as shown in Fig 10 that large pads often have some nonuniformity, however we find that this does not affect usability.

The final step is to cure the ink in a temperature controlled oven at a nominal temperature of 107 °C. We find that even with some oscillation in temperature with an average of 120 °C ±15 °C this method achieves good results. After curing the ink we manually correct any errors that could cause shorts between traces (e.g. stray ink deposited while the head was moving or ink that spread between two closely spaced pads). We note that it is very difficult to remove only a portion of the uncured ink, however after curing an X-acto knife can be used to easily cut away the cured ink in these regions to correct the error.

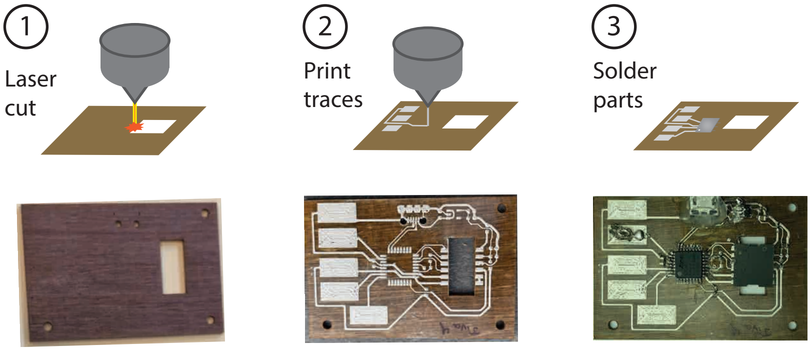
The detailed steps above describe a workflow for producing a circuit with the Voltera circuit printer, however production could be scaled up using screen printing or other large area patterning techniques. This could be used to produce a whole panel of circuits that could then be cut on the laser similar to industrial panelized production of PCBs.

A.3 Circuit assembly and case fabrication

After patterning the circuit the next step is to solder on the electronic components. We do this by hand soldering the parts using a low temperature solder (Sn 42%, Bi 57% Ag 1%). We note that during this process it is important to control the temperature of the soldering iron and achieve best results at 180 °C. At this temperature the process is similar to soldering to copper within a short working time. At higher temperatures of 200 °C or greater we notice a number of issues. First the resin holding together the flax fibers begins to melt. Second, the traces begin to break and delaminate from the board. We notice this same problem occurs when traces are heated for extended periods of time at 180 C. Third, we observe greater probability of cold solder joints and poor adhesion of solder to the traces.

We fabricate the case using a desktop 3D printer (Ultimaker Extended 3). We print cases out of both PLA and PVA which are both standard materials used on fused filament 3D printers. For printing these models we follow the recommended temperature settings on the printer and select the option for breakaway support to enable printing with a single desired material. We observe that the PVA prototype is more brittle and increase the wall thickness

Figure 10: Material comparison. Circuit printed by the Voltera on plywood (left) and Soluboard (right).



Flow v3-compressed.pdf

Figure 11: Fabrication process. Overview of the PCB fabrication process beginning with laser cutting the holes and shape and patterning with the Volterra circuit printer which deposits conductive ink on the surface. The assembly is completed by hand soldering components.

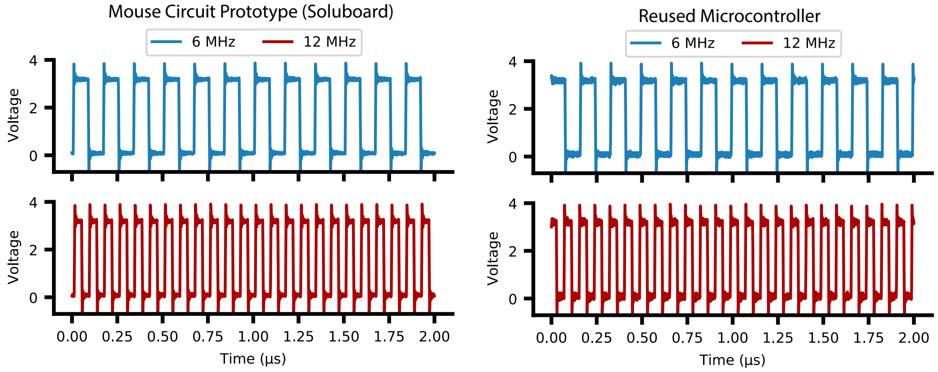


Figure 12: Square wave outputs. Outputs at 6 and 12 MHz from a GPIO pin measured at the end of a trace on different substrates as well as a reused component to evaluate the maximum speed at which signals can be sent.

of the model to accommodate this. In contrast the PLA prototype is much more mechanically robust, but cannot be dissolved in water for disposal and requires an industrial composting process. We print both models in two parts which we join together using PVA glue. We note that materials such as PLA are compatible with standard high volume plastic manufacturing techniques such as injection molding which allows for mass production of parts at extremely low cost.

We perform additional evaluation on our prototypes to investigate whether our traces or substrate affect signal integrity. We program our biodegradable circuit and re-used chip to transmit a square wave at 6 and 12 MHz, which constitute the upper bound of IO operations on the device and capture the output on an oscilloscope. The waveforms shown in Fig 12 shows a close to ideal square wave which explains the good performance in the previous USB speed test. This test shows that at the relatively low MHz frequencies that our microcontroller operates at, the conductivity of the traces does not have an impact. These findings are consistent with prior work using the same conductive paste for prototyping antennas at up to 2.4 GHz [6, 15].