

Circularity in Energy Harvesting Computational "Things"

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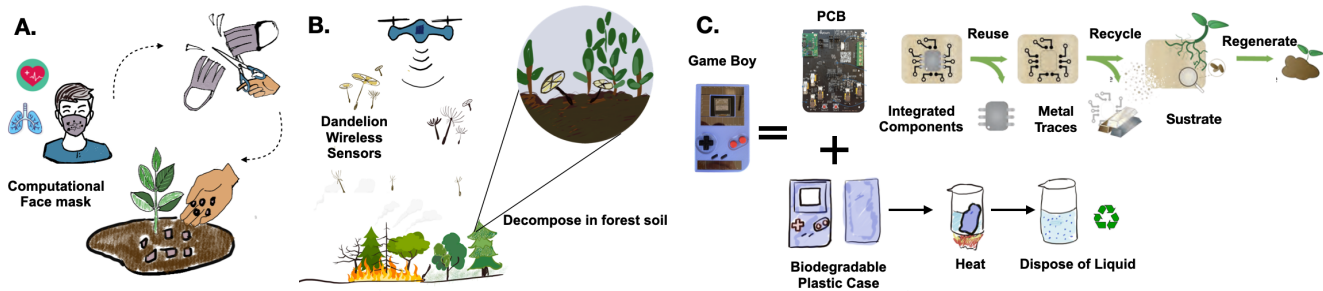


Figure 1: Motivating Applications i) Compostable physiological sensing facemask ii) Dandelion-like wireless smoke sensors that degrade in soil iii) Gameboy with easily recyclable/upcycled components

ABSTRACT

We have witnessed explosive growth in computing devices at all scales, in particular with small wireless devices that can permeate most of our physical world. The IoT industry is helping to fuel this insatiable desire for more and more data. We have to balance this growth with an understanding of its environmental impact. Indeed, the ENSsys community must take leadership in putting sustainability up front as a primary design principle for the future of IoT and related areas, expanding the research mandate beyond the intricacies of the computing systems in isolation to encompass and integrate the materials, new applications, and circular lifecycle of electronics in the IoT. Our call to action is seeded with a circularity-focused computing agenda that demands a cross-stack research program for energy-harvesting computational things.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; • **Hardware** → *Analysis and design of emerging devices and systems*; **Impact on the environment**; *Circuit substrates*.

KEYWORDS

Sustainability, Intermittent Computing, Transient Electronics, Recycle, Upcycle, Circular Electronics, sustainable HCI

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1 INTRODUCTION

The development of energy harvesting and energy-neutral systems (ENS) over the past decade has largely been driven by a push for functionality and low-power operation at scale: to enable a vision of wireless sensing devices that can last for years on a single battery or run battery-free. The confluence of technologies developed by the ENSsys community, including ultra-low power wireless communication [19], advances in energy harvesting [15, 20], and the ability to run sophisticated programs on harvested energy with intermittent computing, [14] has begun to make this vision a reality. With commercial adoption, they have the potential to further fuel the rapid growth of the internet of things (IoT) industry which is expected to increase to a trillion by 2035 [18]. The ability to place computing devices everywhere, however, **raises a new question: what will happen to them at the end of their life? Even the most robust device will eventually become electronic waste (e-waste)**. Global e-waste exceeded is the fastest-growing waste stream and will exceed 74 million metric tons (Mt) by 2030 [6]. E-waste includes hazardous materials like heavy metals and flame retardants, with the potential to pollute groundwater if buried and air when incinerated and pose environmental justice concerns to the surrounding communities [16].

We propose that the ENSsys community integrate environmental sustainability as a core objective for the next decade to develop devices with a fully circular life cycle. For example, intermittent computing objects that are transient in nature can degrade to dust, be recycled, or be recaptured after use. Imagine a computational face mask that measures health data powered by human breath and can be composted after use (Figure 1 a). Likewise, visualize dandelion-like wireless smoke sensors that can be dropped into the forest to detect fires and then disintegrate into the soil (Figure 1 b). Think about playing an interaction-powered game-boy that can be up-cycled back into other electronic devices (Figure 1c) Facemasks [4], Dandelion-sensors [10], and the Battery-Free Gameboy[5] now exist as Energy Neutral Systems (ENS) but do not yet have a circular life cycle. Currently, both the creation and adoption of such circular, battery-free, computationally sophisticated objects is a non-trivial research problem for three reasons:

- (1) **Use of non-biodegradable/ hard-to-recycle materials in functional devices:** Traditional semiconductor processors contain silicon and/or germanium, with plastic substrates and encasing. Similarly, sensors, displays, and harvesters also heavily rely on inorganic material composites. These materials are non-biodegradable and are hard to recycle/upcycle.
- (2) **Lack of developer tool-kits to create circular life cycle battery-free circuits and systems:** While developer toolkits for energy-neutral computing and wireless communicating systems is an active area of research [11, 17], there is a complete lack of electronic design and prototyping toolkits for embedded system developers to create circular computational objects that simultaneously balance circular life cycle concepts like biodegradability, recycling with low/unreliable power operation.
- (3) **Lack of product and interaction design that inspires computational object's recycle/reuse/degradation:** While advances in intermittent computing have inspired a new generation of battery-free, sophisticated, interactive computational objects and wearables, they still generate e-waste. Achieving circularity requires thinking beyond circuits and systems. There is a need for sustainable product design and interaction guidelines to inspire the user to properly recycle/reuse/degrade different electronic/non-electronic parts of the computational object.

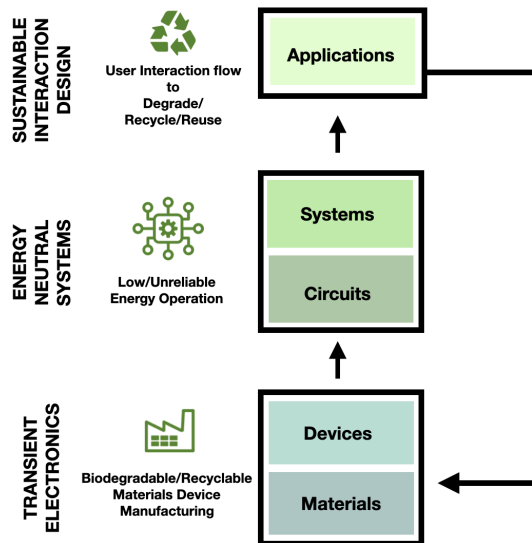


Figure 2: Circular Computing Stack (CCS)

Our Position: In this position paper, we project that overcoming the above limitations requires **rethinking the entire computing stack with circular lifecycle as equally important system design criteria as low/unreliable power operation and functional performance** (Figure 3). The ENSsys community is well positioned to make a significant impact in this domain. Intermittent computing and low-power wireless technologies have already shown that we can eliminate batteries and the challenges they pose for circularity. To go beyond this, we introduce two emerging fields of research that each focus on circularity at a different layer of the computing stack – Transient Electronics at the bottom and Sustainable Interaction Design at the top (section 2). Energy Neutral

Systems (ENS) sit in the middle layer and are focused on power and function. We discuss open research question and strategies for bridging the gaps between these three layers as a way to realize circular energy-neutral computational objects (section 3). Finally, we end with a call to action for the ENSsys Community (section 4).

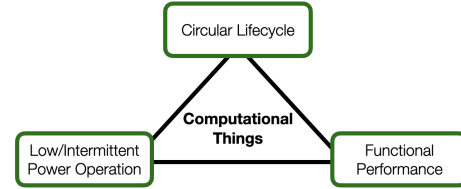


Figure 3: System Design Parameters

2 CIRCULARITY-FOCUSED RESEARCH FIELDS

Transient Electronics

Researchers in chemistry and materials science have explored transient electronics with a focus on identifying or synthesizing biodegradable materials that can be employed for high-performance functional devices [13]. These include fundamental P-type, N-type, dielectric, and substrate materials made from plant material (cellulose, paper, leaves, wood, starch, and alginate), animal (chitosan/chitin, egg whites, silk, gelatin, and peptides) and synthetic protein polymers (PLA, PLGA, PVA, PCL, PHB/V). Interconnects are built using benign metals (Mg, Zn, Mo, Fe, W) or organic conductive polymers (PEDOT: PSS, Mxene)[21]. All these materials chemically or physically dissolve, disintegrate, and degrade into harmless by-products [7]. Examples of transient functional devices include – organic thin film transistors on PLGA substrates, electrochromic displays using gelatin, biodegradable LRC passive elements and memristors, recyclable thermoelectric generators, and super-capacitors. Such rich growing body of work provides a set of physical primitives to serve as the bottom layer in the circular computing stack.

Sustainable Interaction Design

The field of Sustainable Interaction Design focuses on creating products and their life cycle frameworks that enhance recyclability, reusability, and degradability [2, 3]. For targeting the circularity of everyday objects the selection of materials can be made based on the desired life-cycle of the product. Further, sustainable product design adopts materials and parts that are reusable during fabrication [12] or at the end of the product lifecycle [8]. Some strategies have now been applied to electronic objects like mobile phones[9] and peripherals like computer mice[1]. These design principles and applications highlight the technology gaps for the ENSsys community to target.

3 OPEN RESEARCH CHALLENGES

Enabling circularity for the functional computational objects will require intra-disciplinary and iterative dialogue between the Transient Computing, Energy Neutral Systems, and Sustainable Industrial Design researchers to solve the research challenges below.

- (1) **Developer toolkit for transient device, circuit and system performance modeling:** Transient devices can show large fluctuations in conventional system metrics (e.g performance, power) over time. Thus, scaling the creation and adoption of

circular energy-neutral systems requires building circuit design toolkits that can predict degradation of parameters over the system's lifetime. For this, transient devices should be first individually modeled for their degradation with age and then together as a circuit. We hope that such a toolkit can enable creation of complex circuitry like biodegradable microprocessors for intermittent computing applications. It can also help match circular computational objects with appropriate power harvester and harvesting conditions as well as inform the duration of reasonable use of the circular computational object for a particular application scenario.

(2) **Tuning transience: Longevity vs. Degradability** Enabling circularity requires carefully balancing the trade-off of making a device robust enough for functional use while still allowing it to be easily disassembled and degraded at the end of life. Addressing this challenge requires combining novel materials with system-level innovations. For example, if the frequency of a biodegradable transistor is limited, can we design different algorithms and architectures to work within these constraints? Circularity introduces a new set of physical constraints beyond minimizing power for the ENSys community to explore.

(3) **Adaptive runtime programming platform for circular systems.** In addition to designing systems that can run with novel performance constraints, can we also design systems that will adapt to changing conditions? For example, if degradation affects timing functions, could we adjust its algorithm parameters (e.g. FFT window) to compensate? Similarly, these techniques could upcycle degraded components by combining them in novel architectures. This presents an opportunity to build on intermittent computing techniques to enable circularity.

(4) **Product design for circularity** Circular life cycle concepts are not limited to just transient functional devices, circuits and systems but need to be expanded to the product design of the computational object. For example, having a modular assembly of electrical parts and mechanical bodies can ease the complexity of steps and types of processes that are required at the end of the lifecycle. Substrate Materials used in the physical body of the computational object should be biodegradable/Eco-friendly similar to substrates of the functional devices. Further, the physical form factor and interaction design of the computational object should inspire circular interactions like reuse, upcycle, or degradation. For example, a computational face mask can have a quote hidden inside it, just like a fortune cookie, to motivate cutting and decomposition in soil.

4 CALL TO ACTION

In this position paper, we introduce circular computing stack (CCS) as a call to action for the ENSys community to the rising health and climate perils of electronic waste. It provides a road map for ENSys researchers to be flag-bearers in bridging the gap with two emerging research fields, namely, Transient Electronics and Sustainable Interaction Design, to be able to create usable battery-free computationally sophisticated circular objects that can be easily degraded to dust, be recycled, or be recaptured after use.

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