NIVEDITA ARORA | **RESEARCH STATEMENT**

My research envisions creating **sustainable computational materials and things** that operate by harvesting energy from the environment and, at the end of their life cycle, can be responsibly composted or recycled. Picture a disposable face mask that measures health biomarkers, is powered by human breath, and can easily disintegrate into recyclable and biodegradable parts. Imagine an eco-friendly wireless sticky note placed on a refrigerator that is on-demand powered by the heat of a human finger to create contextualized tasks like adding items to the grocery list and can be dissolved in water after use. Visualize agricultural sensors that self-generate power from electrically active microbial communities in the soil to wirelessly communicate water content, pH, and forest fire activity for ecological health monitoring. Building such practically deployable sustainable computational materials require the consideration of four major design parameters:

- **Self-powered computation:** Performs computation or supports interaction using energy harvested from light, heat, vibration, and other ambient sources and may communicate using off-device, low-power backscatter.
- **Form factor:** They should be thin and light to be ubiquitously embedded or retrofitted on everyday objects and surfaces.
- **Low-cost:** Made using simple yet functionally sophisticated circuitry, simple fabrication, and readily available materials for affordability use at scale.
- **Environmental sustainability:** Should be made from materials, along with assembly and packaging, that inspire circular use, reduce carbon footprint, and support energy harvesting to reduce battery waste.

Following these parameters, during my Ph.D., I have built **interactive wireless stickers as the first realized example of the sustainable computational materials vision.** These thin, inexpensive, battery-free interactive stickers can be added to indoor surfaces, such as walls, desks, and program brochures, to sense and provide appropriate feedback for the users' speech, touch, and swipe interactions. My interactive stickers currently follow power, form factor, and cost design parameters, and the research work to re-create its circuitry with end-of-lifecycle aware eco-friendly materials is underway. My sustainable interactive wireless stickers research has appeared in ACM IMWUT, ACM UIST, ACM MobiSys, and Communications of the ACM. It has also won **two best paper awards** (ACM IMWUT, ACM SenSys-ENSSys) **[1, 10], two best poster awards [4, 5],** and has been invited as a research highlight in **SIGMOBILE GetMobile Magazine [3] and Communications of the ACM [2].** In addition, I also have a granted utility patent and three provisional patents as a lead inventor.

***Approach* — Designing for sustainability in computing**, e.g., interactive wireless stickers, requires fundamentally new and disruptive research across all aspects of computing. It opens an exciting research problem space at the materials, systems, and design levels that my research approach addresses with three pillars (Figure 1): (1) *Device fabrication* at the materials level with specific computational, power, and material properties; (2) *Low-power systems* that creatively combine the devices fabricated into functional circuits that can handle low and sporadic power harvested from the surroundings; and (3) *Design of products* and meaningful application scenarios that allow for opportunistic ways of power harvesting and disposal or reuse of computational material. This process is highly iterative and bidirectional; driven by an application scenario, I investigate building new devices and circuits, or sometimes, the realization of functional devices with new properties, I enable new application scenarios. This **research cuts across the boundaries of different disciplines** requiring collaboration with researchers from different fields like materials science, chemical engineering, mechanical, circuits, communication, signal processing, machine learning, HCI, privacy, and industrial design.

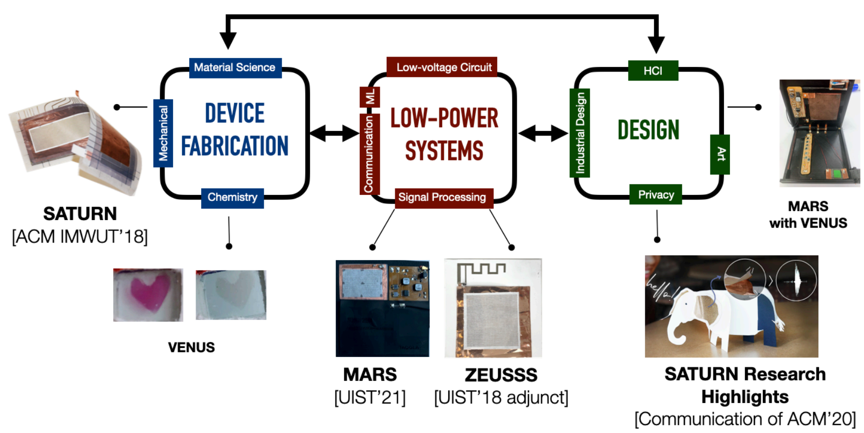

Figure 1. Building sustainable interactive stickers required working at the intersection of fabrication, low-power systems and design

Sustainable Interactive Wireless Stickers

Lending everyday surfaces and objects with interface capability by instrumenting paper stickers onto them allow for the creation of in-situ contextualized tasks, converts them into easily accessible smart controllers, and provides status information. With climate change and e-waste, deploying such computational stickers at a scale, e.g., 10-100 in a building, requires thinking about sustainability, form factor, cost, and what functionality can be achieved within these parameters.

Concretely, in indoor settings, the interactive sticker that allows speech, touch, and swipe gestures should have a size of 50 cm^2, a thickness of 1 mm, and should function with a harvested power budget of 10 µW with circuitry that costs around $1 in bulk. In developing interactive stickers, my research has included **a series of projects with iteratively increasing computational capability (sensing, communication, display)**. I started by fabricating self-powered, thin, and flexible sensors (SATURN), and then I created two ultra-low-power wireless sensing systems (ZEUSSS and MARS). I returned to device fabrication and added an ultra-low-power and voltage display (VENUS) to the wireless sensing system. I am currently re-building SATURN and ZEUSSS with eco-friendly materials, cognizant its end of life. Further, I explore applications for sustainable interaction stickers concurrently with the addition of new functionalities with each project.

I. Thin and flexible self-powered sensors: Sensors often require external power and are encased in rigid packaging. Focussed on power and form factor together, I introduce self-powered thin-flexible audio and vibration sensor **SATURN** (Self-powered Audio Triboelectric Ultra-thin Rollable Nanogenerator) (Figure 2a). It leverages a triboelectric nanogenerator device structure [10] to transform vibrations like speech into an electric signal without any external power source. SATURN is built using everyday materials: paper, thin plastics, copper, and a simple manufacturing process. By exploring different device design parameters like shape, paper hole size, and attachment points between layers, SATURN achieves acoustic sensitivity comparable to an active microphone (ADMP-401) up to 5 kHz. Further, I built a capacitative direction sensor (Figure 2b) that detects surface-based left and right swipes and a barcode-like identity sensor (Figure 2c) that creates a unique pattern of capacitance when a finger is swiped over it.

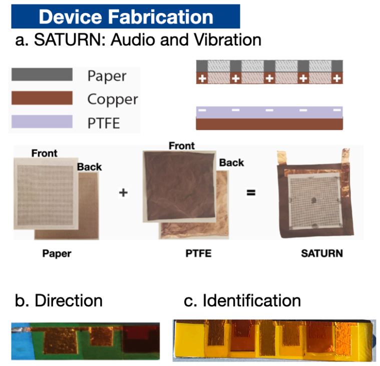

Figure 2. Flexible Thin Sensors

II. Simple, self-sustaining circuitry for wireless communication: The thin, flexible sensors must be embedded in a self-sustaining computational system to build practical applications. I demonstrate this through two projects with increasing functionality, **ZEUSSS** (Zero Energy Sound Sensing Surface) [4] and **MARS** (Multi-object, Ambiently-powered, Real-time Sensing) [6]. To build them, I use two strategies: (1) use of transistors in a non-traditional way—a passive voltage-controlled resistor in the triode region without any bias voltage in ZEUSSS and a specially manufactured zero-voltage-threshold transistor in MARS; and (2) use of backscatter communication where the power-intensive task of carrier radio wave generation is shifted to the transmitter in the infrastructure, leaving the wireless sensing tag with the task of modulating the incoming radio wave based on sensed information and reflecting it to the receiver.

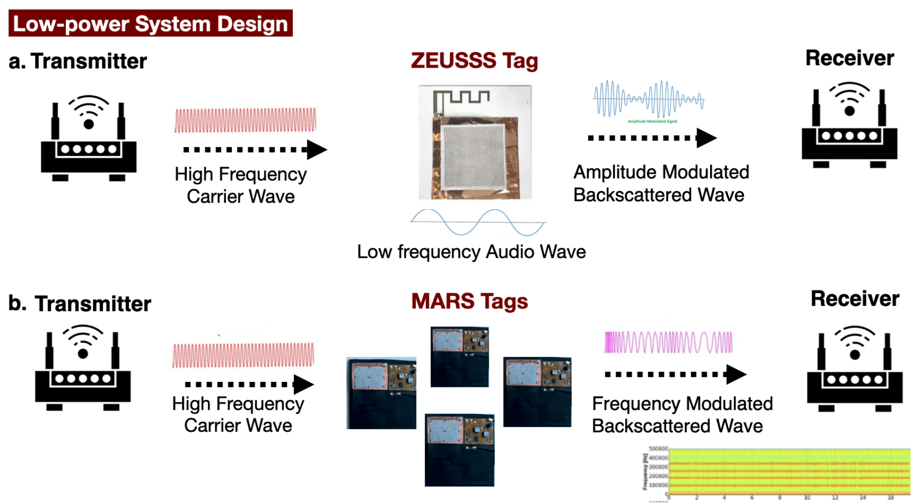

Figure 3. Self-sustaining Wireless Communication with ZEUSSS and MARS

ZEUSSS adds wireless speech communication capability to a single SATURN microphone by leveraging amplitude modulation-based backscatter (Figure 3a). MARS enhances ZEUSSS by providing richer interaction sensing and scalability with frequency modulation-based backscatter communication. MARS demonstrates simultaneous wireless sensing of direction, identity, speech, and touch by multiple interactive stickers in an indoor environment in nano-watts (Figure 3b). Leveraging a zero-threshold transistor and a modified Clapp oscillator circuit design, **MARS consumes < 1 µW power at 380 mV** till 1MHz bandwidth resulting in 2 orders of magnitude improvement over state-of-the-art backscatter communication. It has deceptively **simple circuitry, with just nine components and a bulk cost of $1.40**, including the harvester. The circuitry is kept simple so it can be printable in the future. MARS can be powered by indoor ambient office light (200-500 lux) using two photodiodes or by finger contact on a 6 cm^2 thermoelectric generator. It enables applications like extended microphone stickers for smart home or conference room controls (audio), game controllers (touch), light brightness controls (swipe direction), or food menus for a waiter-less restaurant (swipe-based identification).

III. Thin and ultra-low-power display: To inform the user about active wireless communication adding visual feedback is imperative. Displays are generally the most power-intensive component in an interactive system. For interactive stickers, I leveraged the phenomenon of Electrochromism (EC) and designed VENUS (Vibrant, Electrochromic-display with Nano-ITO for Ultrathin, Self-sustainable-systems) that has an ultra-low startup voltage of **330 mV at 0.6 µW/mm² for a pixel indicator** sufficient to signal on/off to the user (Figure 4). It can be directly controlled by finger-based body heat with a thermoelectric generator or a few photodiodes powered by ambient light without the need for an intermediate driving circuit (which saves cost). VENUS has a simple and scalable fabrication method and is thin and lightweight in form factor.

IV. Transient biodegradable or reusable functional devices: Given that e-waste is the fastest-growing global waste stream, there is a pressing need to reflect on what happens to these computational objects at the end of their lifecycle. I re-think the computing stack from an eco-friendly materials perspective for interactive wireless stickers, where my first endeavor towards this ambitious vision is to recreate the SATURN microphone with biodegradable alternatives. Environmentally hazardous fluoro-polymer-based plastic is replaced with cellulose, and heavy metals like copper are replaced by more benign metals like iron, creating a biodegradable, thin, flexible self-powered microphone.

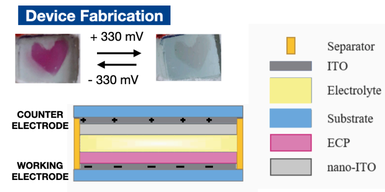

Figure 4. Thin ultra-low-power and voltage electrochromic display

Future Work: Sustainable Computational Materials and Things

My work until now demonstrates sustainable computational materials through the stepwise addition of capability within the specific constraints: a low power budget for self-powered operation; minimal size/thickness for the material form factor; extremely simple circuitry for cost; and eco-friendly materials for circularity. As a faculty member, I want to **work more deeply at the boundaries** of my prior described research pillars with the core agenda of fabricating, designing, and deploying **computing systems with a sustainability-first approach that reduces e-waste, cost, and power**. My effort will focus on three research thrusts.

I. Sustainable devices and circuits: During my Ph.D., my endeavor has been to bridge the sustainable computational materials agenda with different engineering labs' niche innovations and, in the process, also inspire them to be part of the larger sustainable computational materials dialogue. Aa a faculty member, I wish to do the same by collaborating with engineering centers and across departments with a similar focus, as described below.

- ***Tuning device transience (Polymer and Materials Sc)*:** Decisions made at the materials level in the computing stack percolate upwards to the device, circuit, systems, and application layers. Thus, for environmental sustainability, it is pressing to select base materials that allow for the transience of the device, which, based on the application requirements, can be tuned for operating for a certain period and then recycled, reused, or self-degrade at the end of the lifecycle.
- ***Leveraging device structure for low-power (MechE, ChemE, BioE):*** I am interested in exploring new methods of low-power computation that take advantage of material properties and device structure. For example, computational photodetectors [9] use specifically patterned and arranged photodiodes to reduce the burden of computation and power required for activity detection systems.
- ***Low-power bio-degradable computational circuits (Comp Neuro, Materials, EE):*** The non-traditional use of transistors in ZEUSSS and MARS has pushed me to think deeply about analog computing and building neuromorphic circuits for self-sustainable learning based on Spike Neural Networks. Creating such low-power circuits with eco-friendly materials and circularity in mind is an open research question that excites me.

II. Lifecycle and energy-aware programmable systems: The introduction of new types of computational devices (e.g., smartphones, tablets, IoT, smartwatches, and intermittent computing systems) have all driven a reformulation of programming methods. Similarly, programming sustainable computational objects require awareness of their lifecycle and the fact that, at first, the power and performance of transient devices will be different from state-of-the-art. I want to tackle the challenge of how these inadequacies at the materials and device level may be compensated for at the circuits, computer architecture, systems, and algorithm levels.

III. Sustainable Design and Applications:

- ***Finding unique application spaces for sustainable computational materials*:** I am excited to explore applications of sustainable computational things for health, structural health monitoring, industrial monitoring, soft robotics, and environmental health in remote areas like forests. For example, I have demonstrated the extension of interactive stickers beyond indoor interaction sensing applications to the health domain with FaceBit [7], where I physiological monitoring and the potential use of SATURN as a breath-based power harvester embedded inside a mask in collaboration with researchers at NW.
- ***Circular product design:*** Achieving circularity requires thinking beyond just circuits and systems. There is a need for sustainable product design and interaction guidelines that inspire users to properly recycle/reuse/degrade different electronic/non-electronic parts of a computational object. In the long run, such sustainable products should inspire behavioral change toward sustainability in daily life.

- ***User Experience (UX) that sets the right expectation and manages frustration:*** The reduced performance of transient energy-neutral computational objects relative to state-of-the-art will require a shift in users' expectations. Creative UX can be used to manage this frustration but also yield more power from the environment.
- ***Democratization with creative material toolkits****:* I plan to create material toolkits and processes that empower HCI researchers and designers to explore sustainable computational materials as a functional medium and the application scenarios they may support. I will push for a design-driven materials innovation process in which designers are engaged in speculative thinking about the current novel research-grade material devices and prototypes to make them more meaningful, enjoyable, usable, and privacy-aware. I plan to link this research agenda with my teaching.
- ***Sustainability-inspired design and art exhibitions for K-12 students:*** I believe sustainable computational objects can contribute to a larger dialogue about adopting a more eco-friendly lifestyle, improving climate awareness, and supporting justice. For this effort, I plan to collaborate with artists and designers to explore sustainable computational materials as a medium of expression in visual arts installations.

IV. Defining quantitative/qualitative sustainability metrics: As a research community, we must celebrate incorporating sustainability as an equivalent accomplishment to improvements in power or performance. Since we cannot manage what we cannot measure, as a faculty member, I want to work with stakeholders at different levels of the computing stack to define and validate both qualitative and quantitative sustainability metrics for materials, devices, circuits, and effectively smart objects.

A sustainable research community

My research vision of sustainable computational materials aligns with NSF's smart and connected communities and the next generation of sustainable digital infrastructure initiatives. NSF has specifically released DCL for designing for sustainability in computing. In addition, NSF CPS, CISE research programs, and agencies such as the National Renewable Energy Lab and the Department of Energy can be sources of future funding and intellectual support. With the support of the highly interdisciplinary faculty and research centers**,** I would also like to co-develop broader research proposals like the NSF's ASCENT, which specifically value building computing systems starting from materials devices to applications. Sustainability is a grand challenge that can only be solved with collaborative efforts across different research communities. At Georgia Tech, I have been a significant contributing member to the interdisciplinary GT COSMOS (now GT-NU IoM) initiative since its conception six years ago, when I pushed to define the vision and several new collaborations. I have co-organized the Self-SustainableCHI workshop at ACM CHI 2019 [8]. With a similar spirit, as a faculty member, I want to start **creating a larger sustainability dialogue within the different departments and research centers.**

In conclusion, self-sustainable computational materials is a rich and exciting new field of study with many research challenges at the materials, systems, and design levels. I believe an appointment at the department of CS/ECE provides a perfect environment for larger societal impact toward sustainability, peer collaboration and growth in the next stage of my career.

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