Lighting the Reef: Modular Paper Circuits as Ecological Metaphor

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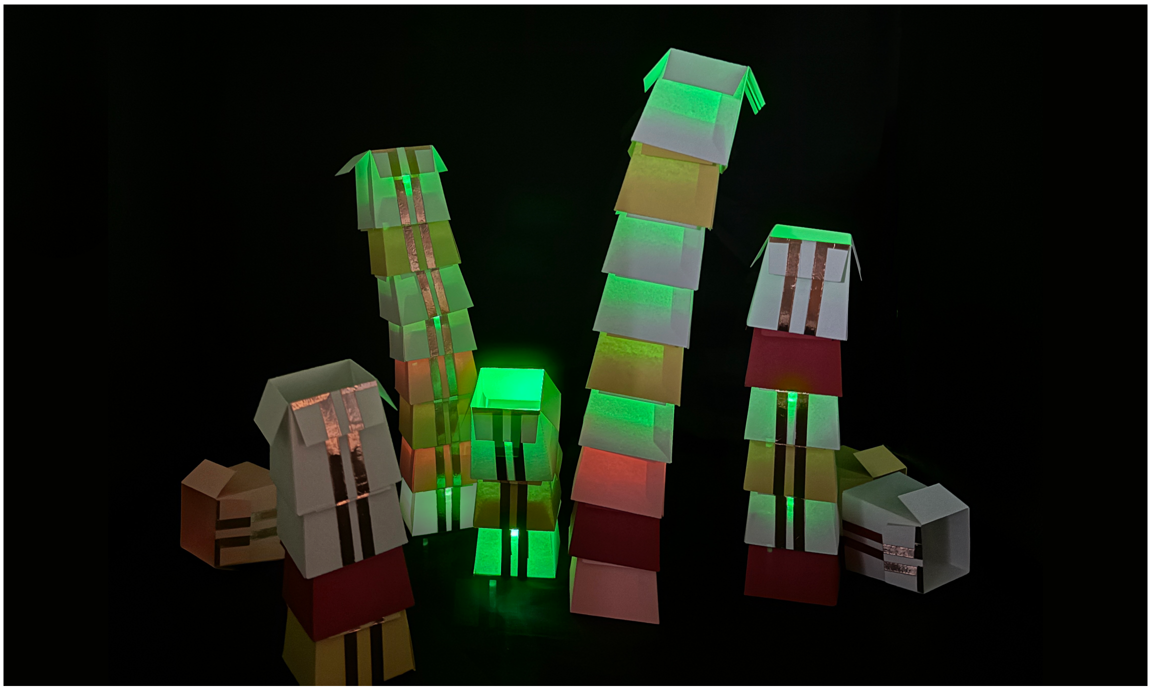

Figure 1: *Lighting the Reef* is a tangible installation built from 3D paper circuit modules, whose illumination depends on alignment and balance. As participants assemble and adjust the blocks, the lights brighten, dim, or turn off, reflecting the changing conditions of the coral system.

Abstract

We present *Lighting the Reef*, an interactive installation that uses modular 3D paper circuits to explore ecological fragility. Participants build coral structures from foldable paper blocks with copper tape and low-voltage components. When connections align, coral modules glow, metaphorically expressing the energy exchange between coral and zooxanthellae, the symbiotic algae crucial to coral metabolism. Pollution modules add resistance that dims light or interrupts the current entirely, mirroring environmental disruption. We position *Lighting the Reef* as a Research through Design case that articulates fragility as an interaction aesthetic and ecological metaphor. We reflect on how modular circuitry, material constraints, and embodied play make precarity tangible. We also report workshops with 15 participants that discussed themes of care, collapse, and interdependence. We contribute insights into designing for fragility with modular circuits, ecological storytelling through tangible interaction, and accessible and reproducible designs for participatory sustainability education.

CCS Concepts

• **Human-centered computing → Interaction design**.

Keywords

Paper Circuits; Sustainability; Tangible Interaction; Physical Computing; Environmental Awareness; Ecological Metaphors; Craft and Materiality

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1 INTRODUCTION

Coral reefs are vital ecosystems that support approximately 25% of all marine species and provide essential services such as coastal protection, fisheries, and livelihoods for millions of people [4]. However, they face urgent threats from rising ocean temperatures, pollution, and overexploitation, necessitating immediate conservation actions to prevent irreversible ecological damage [23]. At the heart of coral survival is a symbiosis. Each coral polyp hosts zooxanthellae, a microscopic algae that supply the coral with energy through photosynthesis, enabling growth and reef-building. In return, the coral provides the algae with shelter and nutrients. This mutualistic relationship is highly sensitive to environmental stress [18]. When oceans warm or pollutants seep in, this delicate relationship breaks down. Corals lose their color, their strength, and ultimately, their life. Known as coral bleaching, this has already become a global crisis [2]. While such ecological knowledge is often presented through data or visualization, interaction design offers opportunities to make fragility felt through embodied experience.

Lighting the Reef investigates how tangible and modular systems can communicate ecological precarity. Participants assemble paper-based coral modules that glow when circuits are connected, but dim or extinguish with pollution elements. Structures are intentionally unstable, requiring care and negotiation to sustain. Participants are asked to build and power coral structures while balancing physical stability and circuit logic. All construction must be done with only the non-dominant hand, which is intended to slow the visitor down and require caution. This mechanic introduces a playful constraint that reinforces the metaphor of ecological fragility. By coupling light, dimming, and collapse to this ecological background, the installation turns the breakdown of symbiosis into a tangible experience of care, stress, and failure. This work is intended for educators, museum facilitators, and public engagement contexts where tangible and low-barrier experiences can provoke ecological reflection.

This work adopts a Research through Design approach [25]. Through cycles of material exploration, prototyping, and workshops, we investigated how fragility can be made tangible and reflective in interaction. The work engages with tangible interactions, embodied and somaesthetic approaches, and sustainability HCI by asking:

- How can modular paper circuits embody ecological fragility?
- How might breakdowns and collapses become reflective moments?
- What does designing with accessible, failure-prone materials offer to sustainability narratives?

2 RELATED WORK

2.1 Paper Circuits and Craft-Based Interaction

Paper has long been used as a material for democratizing and diversifying interaction design. Qi and Buechley's Electronic Popables [20] introduced interactive pop-up books that combined paper engineering with circuits, establishing a foundation for paper computing. Later work, such as Sketching in Circuits [21] and Crafting Technology [3], demonstrated how paper and textiles can serve as expressive substrates for prototyping and education. Beyond education, systems like Circuit Stickers [9] and PaperID [14] highlight paper's potential as a platform for functional and modular interfaces. Other explorations extend paper electronics into three dimensions. Oh et al.'s PEP: 3D Printed Electronic Papercrafts [17] and Gomes and Vertegaal's PaperFold [6] explored how paper's foldability and deformability enable interactive shape-changing artifacts.

Lighting the Reef builds on this lineage by treating paper not only as a low-barrier material, but as one that can be modular, volumetric, and reconfigurable. Our contribution lies less in introducing a new form of paper electronics, but more in using their ease of deformation and structural instability as part of an ecological metaphor. The resulting forms are not meant to be permanent or robust; instead, they invite participants to experience construction as precarious, iterative, and open to collapse.

2.2 Fragility and Aesthetics

Interaction design scholars have argued that breakdowns, imperfections, and instabilities are not defects to be eliminated but opportunities for reflection and care. Hallnäs and Redström's work on Slow Technology [7] and the aesthetics of computational things [8] emphasized how temporal resistance and material imperfection can shift focus from efficiency to reflection. Löwgren [16] extended this by articulating how ambiguity, tension, and breakdown become aesthetic resources in interaction design.

Later research in tangible and embodied interaction has explored how fragility, incompleteness, and resistance can shape reflective engagement. Raffle et al.'s Topobo [22] demonstrated how modular and reconfigurable physical systems encourage experimentation with balance and failure, making instability an integral part of embodied learning. Hornecker and Buur's Tangible Interaction Framework [11] positioned physical engagement and bodily feedback as central to meaning-making, underscoring how tangible interfaces support reflection through manipulation and negotiation. Loke and Robertson articulate "making strange" as an embodied design tactic [15]. It centers first-person movement and disrupts habituated routines to sustain attentive kinaesthetic reflection. These works reframe tangible interaction as a practice of continuous adjustment, where instability, resistance, and imperfection invite care, reflection, and embodied attentiveness.

Our installation aligns with this trajectory. *Lighting the Reef* treats systemic fragility and reconfiguration not as failure, but as an experiential condition through which ecological interdependence becomes tangible. Circuits fail if modules are misaligned; structures collapse if stacked too high; light dims under resistive blocks. The instability of stacked paper modules, their tendency to collapse or fail electrically, is not framed as a limitation but as a central metaphor for ecological precarity.

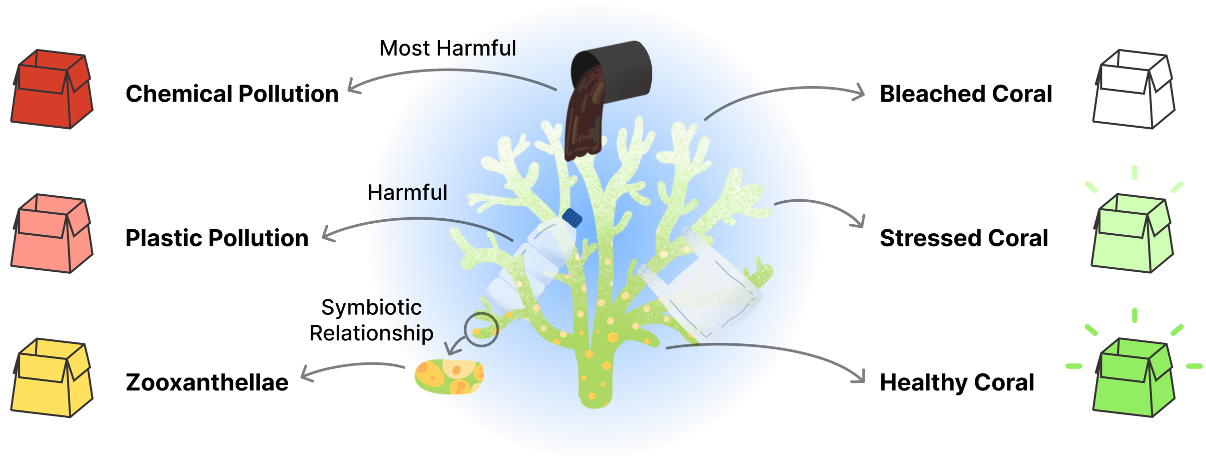

Figure 2: Visual metaphor mapping between paper circuit modules and coral ecosystem.

2.3 Sustainability, Ecological Metaphors, and Data Physicalization

HCI has increasingly explored how design can foster reflection on ecological issues. Early work in Sustainable HCI has framed design as a medium for reflecting on ecological values and material consequences [1]. Eco-feedback research has used ambient and tangible feedback to connect everyday actions to environmental impact, as surveyed by Froehlich et al. [5]. Other work has employed metaphor and visualization to connect human activity with ecological fragility. Kim et al.'s Coralog [13] used a coral reef metaphor to visualize personal micro-activities and their environmental consequences, bridging abstract data with ecological imagery. Holmes [10] framed eco-visualization as a combination of art and technology for sustainability reflection.

Meanwhile, research in data physicalization has shown how constructing physical representations of data can support reflection, dialogue, and embodied reasoning. Constructive Visualization [12] argues that building with modular physical components supports embodied reasoning by enabling people to externalize and manipulate relationships that would otherwise remain abstract. Perovich et al. ([19]) demonstrate how situated physicalization of environmental contaminants can invite community-driven inquiry. Thudt et al. ([24]) highlight how personal physicalization supports self-reflection through hands-on construction. These works show that meaning emerges not only from representation, but from the act of assembling, adjusting, or repairing physical structures.

Lighting the Reef contributes to this discourse by introducing an ecological physicalization in which the "data" is not numerical but metaphorical. The coral health, pollution stress, and system fragility are enacted through brightness, connectivity, and structural stability. Rather than mapping external datasets, our system foregrounds ecological logic and interdependence as manipulable physical relationships. By combining tangible modules with embodied constraints, the installation becomes a constructive physicalization of ecological precarity. This positions our installation as a form of ecological physicalization, where circuit behavior and structural negotiation collectively stand in for dynamic environmental processes.

3 DESIGN OVERVIEW

3.1 Design Motivation

Building on the ecological background, our design motivation was to translate coral precarity into an experience that is negotiated through material interaction rather than explained through static representation. We asked how people might come to feel the tension between thriving and collapse by assembling, adjusting, and repairing a physical system. This led us to focus on interaction qualities that could stand in for ecological dynamics, such as the ease with which structures become unstable, the sensitivity of circuits to small misalignments, and the need for ongoing maintenance to keep the reef "alive."

We chose paper, copper tape, and low-voltage components as core materials. This is not only because they are inexpensive and accessible, but also because their mechanical and electrical properties resonate with the theme of fragility. Paper bends, deforms, and wears. Copper contacts can flicker or fail if they are not carefully aligned. These characteristics informed our shift from flat paper circuits to stackable 3D modules, where physical topology and electrical continuity determine one another.

Rather than aiming to simulate coral ecosystems in detail, we intend to construct a situation in which participants experience precarity through the effort of building, balancing, and sustaining light. This framing guided the design of module geometry, and the choice to work with failure-prone connections. The introduction of the non-dominant hand rule slows action and emphasizes careful adjustment. This constraint is grounded in embodied design theory, particularly Loke and Robertson's notion of "making strange" [15], which suggests that disrupting habitual movement patterns can heighten kinaesthetic awareness. By slowing gestures and reducing precision, the non-dominant hand foregrounds care, attentiveness, and the ever-present risk of collapse. These qualities are central to the ecological metaphor.

3.2 Design Goals and Principles

Lighting the Reef translates coral survival into a tangible and participatory experience. Our technical development is grounded in three goals, **accessibility, metaphorical clarity, and modular interactivity,** that together shape both the material construction and the audience experience.

Accessibility. We intentionally minimize technical barriers so that the system can be replicated by educators, students, and museum facilitators without specialized infrastructure. All modules are fabricated from white cardstock, copper tape, CR2032 coin-cell batteries, and basic low-voltage components. No soldering, special tools, or programming are required. This approach prioritizes reproducibility and repairability. Participants can open, re-tape, and reassemble blocks during workshops, turning construction and maintenance into part of the learning experience.

Metaphorical clarity. Each block maps one-to-one to a real-world ecological role so that the system's behavior is legible through action. Figure 2 depicts the mapping between physical modules and coral ecosystem dynamics:

- **Coral blocks** (white): paper modules with embedded green LEDs that glow when the reef is powered and structurally intact, signaling a thriving state.
- **Zooxanthellae blocks** (yellow): power modules housing coin-cell batteries that feed the surrounding coral through copper interfaces.
- **Pollution blocks** represent environmental stressors: pink (plastic pollution blocks) adds resistance and visibly dims the LEDs, while red (chemical pollution blocks) breaks connectivity entirely.

This explicit mapping ensures that participants can immediately distinguish block types and infer causal relationships, understanding what sustains coral reefs, what causes their degradation, and how different configuration choices will impact outcomes.

Modular interactivity. The installation is constructed from reconfigurable, stackable modules so that form-finding, electrical continuity, and collapse are negotiated in real time. As structures grow in size and complexity, participants must manage both physical balance and circuit logic: a coral that fails to connect or collapses will not glow. An embodied constraint, using only the non-dominant hand, slows interaction and heightens attentiveness, foregrounding precision and care as central to ecological intervention. The resulting experience invites iterative experimentation, where adding or removing pollution, relocating power, or rebuilding after failure becomes a reflective practice rather than a discrete task.

Across these design goals, the system operationalizes fragility as an interaction quality. Brightness becomes a proxy for ecological vitality, dimming signals accumulating stress, and darkness marks breakdown. By keeping materials simple and the logic legible, the installation supports quick entry, sustained exploration, and meaningful discussion about interdependence and care.

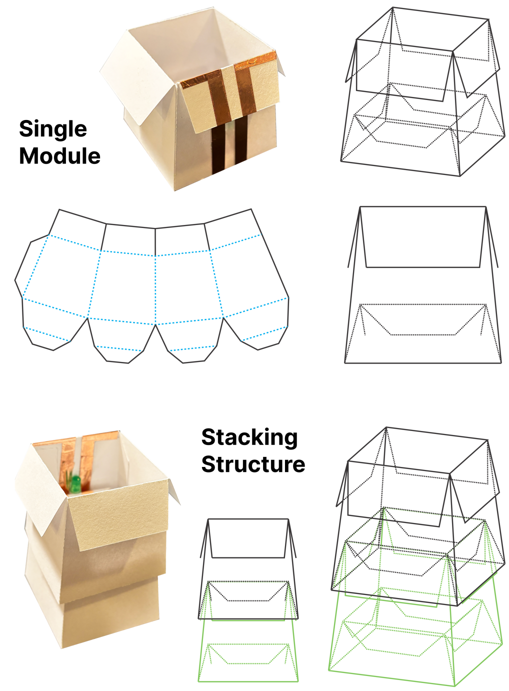

Figure 3: Structural design of the coral module.

3.3 Structural Form and Iteration

We crafted each block using 65lb Cover (176 gsm) cardstock, folded into truncated pyramid shapes. We laid copper tape on both the inner and outer surfaces to create conductive paths and added electronic components to the inside of the module. We also added terminals at the top and bottom for dual-directional connections. As illustrated in Figure 3, each module is designed with foldable tabs that align vertically when stacked. These tabs ensure stable mechanical contact and electrical continuity by applying gentle pressure between copper tape terminals. The unfolded template, completed blocks, and transparent views in the figure show how structural geometry and conductive layout work in tandem to support reconfigurable circuit logic.

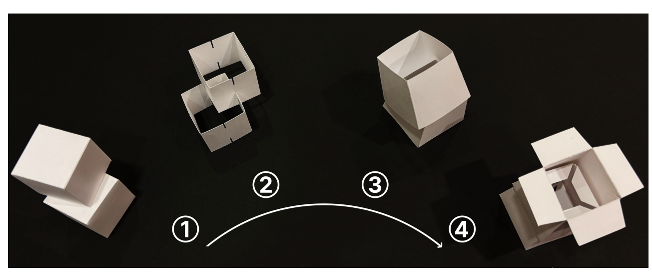

Figure 4: Structural design iterations of modular coral bricks.

Our design process began by transforming flat paper circuits into stackable 3D forms. Our earliest prototypes took the form of closed cubes (Figure 4 (1)). While straightforward to fabricate, they were mechanically unstable when stacked and often resulted in unreliable circuit contact. To address that, we removed the top and bottom faces and introduced notched slots to interlock the blocks (Figure 4 (2)). This improved structural alignment and enhanced electrical connectivity, but increased fabrication complexity. We then explored truncated pyramids for their mechanical stackability and visual resemblance to coral reefs (Figure 4 (3)). These shapes nested smoothly, improving alignment and simplifying handling. However, the smooth fit reduced the surface pressure needed for reliable circuit closure. We ended up adding folded paper tabs to both ends of the pyramids (Figure 4 (4)). This created a structure that uses the elasticity of paper itself to maintain pressure and circuit closure. These tabs compress gently when stacked, creating consistent copper-to-copper contact.

This final structure extends the affordances of paper circuits into 3D, enabling continuous electrical flow in modular, reconfigurable systems that can be freely assembled and disassembled by participants. Through these iterations, we also came to recognize that structure is another major factor contributing to fragility beyond the material itself. Small variations in angle, tab pressure, and stacking height produced visibly different electrical outcomes, from steady illumination to dimming or flicker. This sensitivity emerged from how form distributes force and alignment in the vertical stack, making structural geometry itself a driver of the interaction aesthetic.

In this sense, the iterative process clarified how mechanical configuration shapes the perceptibility of ecological metaphor. The modules needed to be stable enough to support block constructions, yet delicate enough that imbalance, misalignment, and gradual drift were meaningfully felt. These constraints guided our final geometry design, a form that supports stacking while preserving the instabilities through which fragility becomes sensible.

3.4 Embedded Circuits and Fabrication Approach

We developed four core block types, each designed to embody both a specific ecological metaphor and a functional role within the circuit (Figure 5). Each type of block contributes a distinct behavior to the overall system, enabling participants to reason about ecological balance through physical configuration and electrical interaction:

- **White Coral Blocks** contain green LEDs embedded inside the paper shell. They illuminate when connected to power sources (the zooxanthellae blocks), representing healthy and thriving coral structures.
- **Yellow Zooxanthellae Blocks** house CR2032 coin-cell batteries that provide power bidirectionally, both upward and downward through the stack. These serve as the energetic foundation of the reef.
- **Pink Plastic Pollution Blocks** integrate 220-ohm resistors, adding resistance that reduces brightness and partially obstructs the electrical flow. The dimmed glow symbolizes the gradual degradation of coral vitality.
- **Red Chemical Pollution Blocks** are intentionally non-conductive, interrupting current flow entirely. Power can only be restored by placing a zooxanthellae block above or below, creating a literal and metaphorical act of ecological repair.

Each configuration is both visually and functionally legible, helping participants intuitively link cause and effect. Through the interactions, they would understand how power circulates, how fragility manifests, and how human intervention can restore or disrupt balance. The use of color-coded and material distinctions turns the physical act of building into a process of situated reasoning.

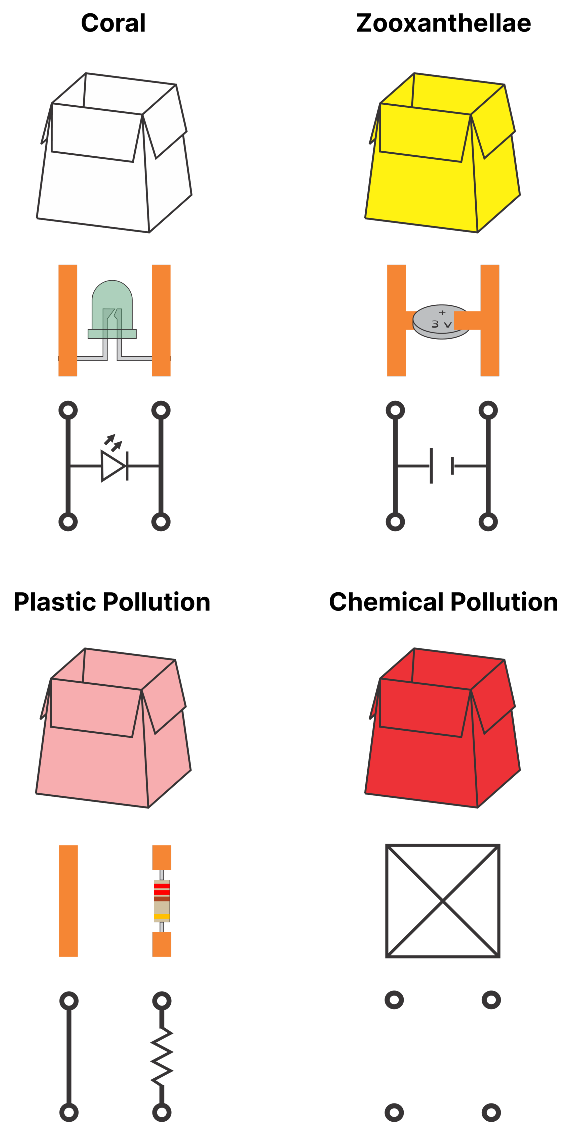

Figure 5: The four block types and their effects on electrical connectivity.

To illustrate how these module types behave when combined, Figure 6 presents three representative stacking configurations. Each arrangement demonstrates how the position and type of a block could change the electrical path running vertically through the structure. When a coral module sits directly above a zooxanthellae block, the copper interfaces align to form a complete circuit, producing a bright, stable illumination. Introducing a plastic pollution block adds a series resistor that reduces current, causing the coral module to glow more faintly. A chemical pollution block then introduces a full break in the circuit. With no conductive path available, the coral cannot light at all. These examples show how stacking becomes a form of ecological reasoning, enabling participants to explore thriving, stress, and collapse through the physical and electrical dependencies of the modules.

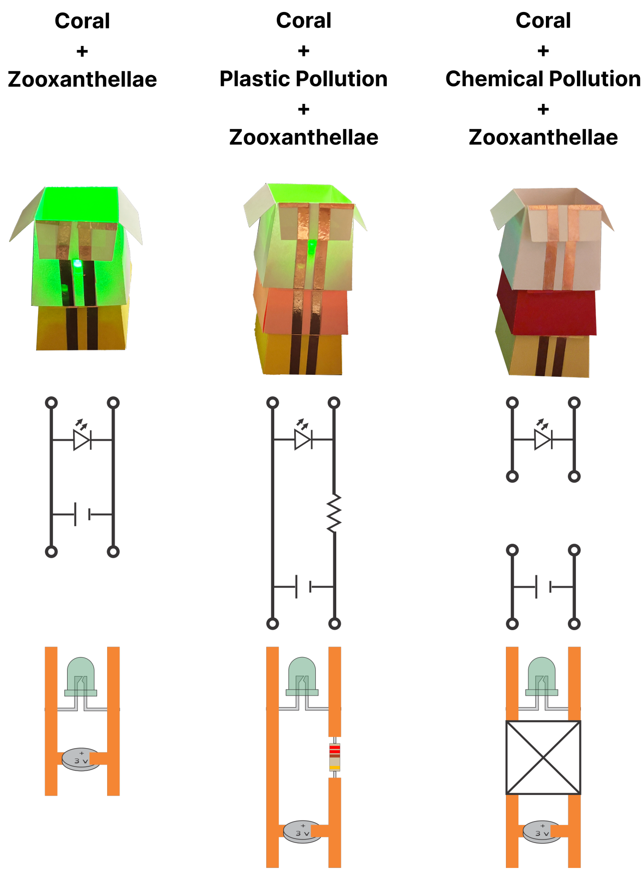

Figure 6: Example stacking configurations and their corresponding behaviors.

Electronic components are affixed directly onto paper using copper tape, forming conductive pathways without soldering or adhesives. This technique preserves the flexibility of the paper, enabling modules to be folded, unfolded, and reassembled repeatedly. Figure 7 illustrates how internal LED and resistor connections align with copper traces, ensuring contact through pressure rather than permanent bonding. Participants can peel and reposition components as part of their exploration, transforming assembly into an iterative and reflective act.

Figure 7: Internal structure of a coral module.

To support reproducibility, we created printable templates that guide users through hand-cutting and folding each module. The fabrication process is intentionally low-tech, using only everyday tools such as scissors. We deliberately avoided processes such as laser cutting or conductive ink printing, emphasizing accessibility. These decisions align with our goal of designing for educators, learners, and informal makers who can replicate or remix the system without specialized equipment.

Our approach builds on a lineage of craft-based interaction design and paper electronics. The project draws inspiration from Buechley and Qi's foundational work on paper circuits [21], explorations of crafting with electronics [3], and especially Electronic Popables [20], which demonstrated the expressive potential of interactive paper. By extending these ideas into a reconfigurable three-dimensional form, *Lighting the Reef* expands the expressive and pedagogical possibilities of paper circuitry, merging ecological storytelling with tangible, material interaction.

4 INTERACTION AND EXPERIENCE

The installation offers open-ended interaction. Participants can make their own choices or roll a die to introduce chance. They build with coral and zooxanthellae blocks and observe real-time feedback through LED illumination. They also insert or remove pollution blocks to see circuit responses, or reconfigure the order and position of modules to explore alternate outcomes. This interaction is not competitive or goal-oriented. It supports quiet reflection, embodied learning, and iterative discovery. As participants contribute to the structure, the reef grows while also becoming more unstable and fragile, which simulates ecological accumulation and stress. The installation can be reset, repaired, or allowed to grow organically across an exhibition.

4.1 Methodology

We evaluated *Lighting the Reef* in two workshops conducted in our university makerspace that functioned as an informal learning setting. Our evaluation followed the research through design methodology [25], in which workshop encounters served as situated probes. Rather than testing predefined hypotheses, we observed how participants interpreted module roles, negotiated instability, and engaged in repair, using these encounters to generate design-relevant insights. Figure 8 shows examples of participant constructions.

We recruited fifteen participants aged 20 to 60 with varied making experience, as educators and informal learners are the primary audiences for whom this toolkit is intended. Sessions were lightly facilitated. Participants received only a brief demonstration of block types and were then encouraged to explore independently. Before starting, each participant received a brief explanation of the activity and its purpose, provided informed consent, and could opt out at any time. We did not collect identifying or sensitive data, and we photographed only with explicit permission.

We documented interactions through notes and photographs, focusing on how participants inferred metaphorical mappings, negotiated failures, and adapted to the embodied constraint. This methodological stance emphasises situated interpretation and design insight rather than controlled comparison.

4.2 Observations

Across both sessions, most participants intuitively grasped the relationships among power, pollution, and coral health after several minutes of exploration. Many commented on the fragile feeling of the structure, which aligned with our goal of making ecological precarity tangible. Participants frequently reconfigured designs, tested alternative stackings, and learned through cycles of failure and repair. These behaviors demonstrate how fragility and the requirement to maintain alignment can transform manipulation into an act of care.

One participant, shown in the upper left of Figure 8, explicitly attempted to "build as high as possible" with a single yellow zooxanthellae block to see how many coral blocks it could support. As the stack grew, coral blocks began to dim and intermittent connections appeared, prompting discussion among nearby observers about limited resources, load distribution, and thresholds of collapse. This behavior illustrates how the coupling of physical topology and electrical continuity can scaffold exploratory reasoning about interdependence. Participants did not treat failures as an endpoint, but rather treated dimming and instability as signals to probe, adjust, or test hypotheses about how the system behaved.

We also observed collaborative repair behaviors. Pairs and small groups negotiated who stabilized the stack and who adjusted terminals, often narrating their reasoning aloud. Participants reported that the non-dominant hand constraint slowed them down and made them more careful, reinforcing our intention that bodily resistance would foreground attentiveness and precision. These patterns suggest that fragility, constraint, and reconfiguration can transform technical manipulation into participatory storytelling about resilience and care, linking material engagement with ecological reflection.

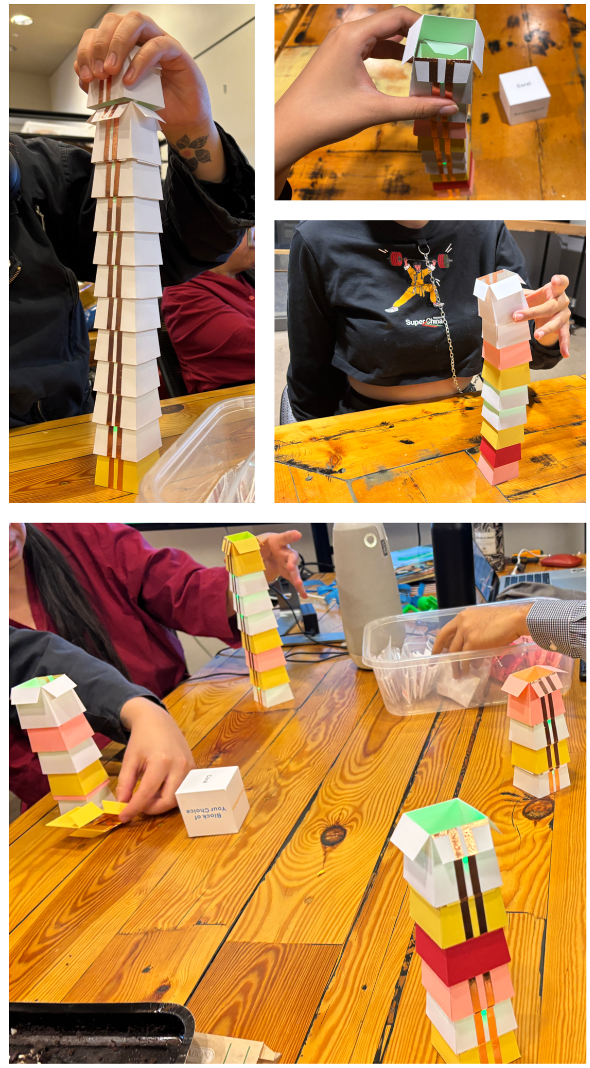

Figure 8: Participants interact with modular coral blocks during the workshop sessions.

5 DISCUSSION

Our observations clarify how participants' behaviors aligned with the interaction qualities we designed for. Participants rapidly identified the roles of coral, zooxanthellae, and pollution modules, indicating that the mapping between components and ecological concepts supported immediate interpretability. They frequently reorganized stacks, diagnosed flickering or dimming LEDs, and engaged in collaborative repair when modules collapsed. These actions indicate that the system's fragility was not mistaken as a technical failure, but rather perceived as part of the interaction.

The fragility of the paper modules prompted slower and more deliberate movements, directly supporting our aim to foreground care, attention, and maintenance in the interaction. The non-dominant hand rule amplified this effect by reducing precision and prompting participants to adjust their pace, consistent with embodied interaction research that describes how constraint can heighten kinaesthetic awareness. This aligns with prior work in constructive and situated data physicalization, where assembling and adjusting physical elements contributes to reflective sensemaking. Unlike previous work, our system places breakdown and repair at the center of building, extending physicalization research toward fragility as a primary interaction aesthetic.

These findings also contribute several forms of design knowledge. First, they articulate fragility as an interaction quality operationalized through structural sensitivity rather than material symbolism alone. Second, they outline a transferable pattern in which physical topology and electrical continuity determine one another, enabling breakdown, repair, and alignment to function as expressive states within the interaction. Third, they demonstrate how low-threshold systems can support exploratory and collaborative reasoning, with participants treating instability as an opportunity for inquiry and shared care.

The ecological simplification of the system is intentional. Real coral ecosystems involve multiple stressors across long timescales, yet such complexity can overwhelm short workshop encounters or informal learning settings. Simplification supports immediate understanding while enabling participants to iteratively build, disrupt, and repair the system, making ecological precarity accessible as an embodied metaphor rather than a representational simulation. Our contribution therefore lies not in ecological fidelity, but in exploring how interactive fragility and repair can evoke ecological thinking through physical engagement. In the spirit of research through design, our insights contribute not universal claims, but generative design patterns and experiential qualities that others may adapt to related ecological or fragile systems.

6 FUTURE WORK

Several directions for extending the system emerge directly from participants' behaviors and interpretations during the workshops. Participants repeatedly treated dimming and flicker as meaningful indicators of ecological stress, which motivates our exploration of temporal dynamics such as gradual bleaching, recovery sequences, or cascading failures triggered by instability or accumulated resistance. Introducing lightweight sensing of tilt or micro motion would enable the system to express these changes over time without increasing fabrication complexity.

Participants also described the softness and vulnerability of the paper modules as characteristic of coral fragility, informing our interest in experimenting with biodegradable or translucent substrates that heighten this material expressiveness while remaining accessible for public making.

Beyond material and design refinement, participants' frequent collaborative repair efforts point toward future studies of how people negotiate shared ecological responsibility. Building on work in constructive and situated data physicalization, future work could explore how different grouping configurations influence people's understanding of interdependence and repair. Deployments in classrooms and museums will further help understanding how these patterns evolve in longer engagements and how learners narrate ecological processes through hands-on reconstruction. Finally, we will package the system as a replicable toolkit so that educators and facilitators can adapt the metaphor to local contexts.

7 CONCLUSION

Lighting the Reef offers a reproducible approach to ecological storytelling with paper electronics, and demonstrates how fragility can operate as an interaction quality. By coupling physical and electrical topology, the system extends prior work in tangible interaction and constructive data physicalization, showing that instability and breakdown can serve as expressive and reflective elements. Workshop observations further highlight how participants interpreted dimming, flicker, and collapse as meaningful ecological cues, suggesting that material sensitivity and embodied constraint can support intuitive reasoning about interdependence and stress.

The project remains intentionally open to remix and extension. We invite the TEI community to adapt and extend these modules and methods, helping learners and visitors construct, dim, and repair their own reefs, and to encounter ecological precarity as something that is felt through the hands as well as understood by the mind.

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