# Designing Living Artefacts for Multispecies Interactions: *An Ecological Approach*

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Living systems are not only characterised by the sum of individual organisms but also by the multispecies interactions that occur among them, which are crucial for self-regulation, versatility and the evolution of life. Within the fields of biodesign and biological HCI, designers and researchers have strived to facilitate and mimic the qualities that these multispecies interactions entail. However, designing in a way that can account for such intricate dynamic systems presents significant challenges, necessitating alternative approaches that offer greater nuance and sensitivity to natural ecosystems. By incorporating living organisms as interactive components within human-made systems, *living artefacts* provide an opportunity to explore and design with such sensitivity. Leveraging the inherent interactive potential of living organisms, we propose an ecologically oriented design approach in which living artefacts are recognised and supported within the context of an intricate web of life. To this end, we conducted an in-depth analysis of existing living artefacts, paying particular attention to the *multiplicity, connectivity* and *reciprocity* of interactions between humans, other living entities and computers. From this analysis, we identified three distinct types of multispecies interactions that help to articulate and leverage their unique features within, across and beyond living artefacts.

***Keywords*** – Biodesign, Biological HCI, Living Artefacts, Multispecies Interactions, More-than-human, Sustainability.

***Relevance to Design Practice*** – This paper presents multispecies interactions as a viable concept for designers and emphasises the role of living artefacts in facilitating such interactions. Additionally, it highlights their contribution to promoting the care of all living entities and fostering sensitivity to natural ecosystems.

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## Introduction

Natural life is not merely a collection of individuals but an interconnected system or web (Margulis & Fester, 1991; Margulis & Lovelock, 1974). Whether in a forest, a coral reef, or the human microbiome, a diverse set of species is engaged in a constant state of entanglement within every naturally occurring living system (Gilbert et al., 2012; Margulis & Fester, 1991). As more ecologists, anthropologists and philosophers recognise that humanity is also part of this entangled web of life, many have suggested that we should no longer differentiate between nature and culture and instead adopt a perspective that transcends anthropocentrism to ensure collaborative survival (Chakrabarty, 2009; De la Bellacasa, 2017; Escobar, 1999; Haraway, 2016; Latour, 2017; Lowenhaupt Tsing, 2015; Morton, 2018).

Driven by these ecological viewpoints and informed by our personal experiences in biodesign practices (Myers, 2014) with living organisms, we explore the concept of *multispecies interactions*, which we define in this paper as *the intricate interplay involving at least two species, encompassing both humans and non-humans (i.e., multiplicity), in varying degrees of connectivity and reciprocity*. We draw on ecological principles to define *multiplicity* and *connectivity*, which are essential for describing the diversity and occurrence of multispecies interactions (e.g., Doolittle & Booth, 2017; Schwartz et al., 2000). Our understanding of *reciprocity* is inspired by ongoing discourses in biodesign (e.g., Armstrong, 2022; Karana, McQuillan et al., 2023) and *more-than-human* design (e.g., Forlano, 2016; Giaccardi & Redström, 2020; J. Liu et al., 2018). In this paper, we emphasise reciprocity as a guiding principle for how multiplicity and connectivity should be realised, directing multispecies interactions towards socially, environmentally and ethically sound outcomes.

In the realm of the natural sciences and ecology, multispecies interactions are considered essential for sustaining the fitness of living systems by contributing to self-regulation, versatility and the evolution of life (Gilbert et al., 2012; Holland & DeAngelis, 2010; Margulis & Fester, 1991; Schwartz et al., 2000). These attributes have been extensively discussed in sustainability initiatives across multiple fields, including design and architecture (e.g., Forlano, 2016; Karana, McQuillan et al., 2023; Keune, 2021; Littman, 2009), Human-computer Interaction (HCI) (e.g., J. Liu, et al., 2018; Liu et al., 2019; Smith et al., 2017), and materials science (Gilbert et al., 2021). More recently, biodesign scholars have sought to

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incorporate these attributes into their respective practices, regarding living organisms as important components of interactive systems (Pataranutaporn et al., 2020) that remain alive throughout their use time, which are referred to as *living artefacts* (Karana et al., 2020). To align with this approach, several frameworks have been proposed and utilised to support such biodesign endeavours (e.g., Karana et al., 2020; Karana McQuillan et al., 2023; Kim et al., 2023; Merritt et al., 2020; Pataranutaporn et al., 2020). However, despite this growing interest and discourse, a more nuanced approach that embraces multiple species and investigates how their interactions benefit the design of living artefacts remains relatively unexplored.

In an effort to bridge this gap, this paper analyses the potential for living artefacts to become integrated into both daily life and (equally importantly) non-human ecosystems, fostering interactions between diverse species. Specifically, we propose the concept of *multispecies interactions* as a guiding ecological approach for the designers of living artefacts across design and HCI, encouraging them to reflect on their practices and consider human de-centred and other alternative approaches for engaging with the intricate systems that comprise the web of life.

To develop our approach, we undertook a systematic review involving the collection and screening of living artefacts, followed by an in-depth analysis that utilised ecologically inspired interaction webs to visualise multispecies interactions. Based on this analysis, we introduce three distinct yet interlinked types of multispecies interactions with, and through, living artefacts: 1) *within the artefact*; 2) *across the artefact with non-humans*; and 3) *across the artefact with humans*. Drawing from our study and existing design, HCI, biology and ecology literature on multispecies interactions, we provide a corresponding vocabulary to explore diverse facets of these interaction types in relation to the multiplicity, connectivity and reciprocity.

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**Raphael Kim**, Ph.D., is an independent researcher, writer, and educator specialising in biodesign. He previously served as a postdoctoral researcher at the Materials Experience Lab, TU Delft. Raphael's research explores innovative methods for biodesigners to work with microbes and DNA, focusing on developing sustainable and ecological design outcomes. His interdisciplinary approach aims to integrate biological systems into design practices, promoting advancements in sustainable futures. He continues to contribute to the field through his ongoing research, writing and educational efforts, helping to drive the conversation at the intersection of biology and design.

**Elvin Karana** is a Professor of Materials Innovation and Design at TU Delft. Her research delves into the synergistic collaborations among design, biotechnology and materials science, aiming to develop innovative biomaterials that can be seamlessly integrated into daily human life and aligned with the diverse cycles, scales and temporalities of ecosystems. In 2019, Elvin established the Material Incubator lab in Den Bosch, and in 2022, she founded the Delft-Biodesign Lab at TU Delft. These laboratories focus on developing tools and methodologies to deepen our understanding of microorganisms in biodesign and to promote regenerative design principles in the creation of living artefacts. Since 2015, Elvin has been co-directing the Materials Experience Lab, contributing to research on human-material relationships. She is the co-founder of the Centre of Design Research for Regenerative Material Ecologies, which explores the potential of material-driven design for planetary well-being.

## Related Works

### Multispecies Interactions: *Ecological and Social Accounts*

In recent years, advances in DNA analysis techniques have blurred the definition of what is considered a biological individual (Gilbert et al., 2012). For example, our 'human' bodies host billions of microbial cells that are critical to our survival (Heintz-Buschart & Wilmes, 2018), our 'human' cells contain organelles that carry DNA of bacterial origin (Pallen, 2011), and even about 8% of the DNA that comprises our own 'surely human' genome originated from viruses, passed down through many generations (Burn et al., 2022). In essence, humans and other animals are now increasingly recognised as *holobionts*, i.e., assemblages of a host and the various species living in, on or around it (Gilbert et al., 2012). This concept of living organisms as assemblages rather than individuals applies to all sorts and scales of life. Plants cannot exist without their mycorrhizal partners (Bonfante & Anca, 2009), and lichens challenge binary notions of individuality even further (Griffiths, 2015).

In this context, symbiosis—whether mutualistic, commensalistic or parasitic (Douglas, 2021)—is understood to be a quintessential quality of life that enhances biodiversity and the functionality of ecosystems (Holland & DeAngelis, 2010; Schwartz et al., 2000). The late Lynn Margulis advocated the idea that symbiosis is an essential driver of evolution, from the development of eukaryotic life to that of modern terrestrial ecosystems (Margulis & Fester, 1991). Lovelock and Margulis (Lovelock, 2016; Margulis & Lovelock, 1974) extended this notion with their *Gaia Hypothesis*, in which the entire biosphere is envisioned as a single interconnected living entity. Although this view of the earth as a self-regulating superorganism has invited significant criticism over the years, it nonetheless vividly illustrates how life is entangled at all scales, from an individual cell to an entire ecosystem.

On this point, ecologists, anthropologists and philosophers argue that the reductionist view of life is at the root of many anthropogenic issues prevalent today (Chakrabarty, 2009; Escobar, 1999; Latour, 2017; De la Bellacasa, 2017; Morton, 2018). Tsing (2015) contends that instead of viewing life as a collection of individuals, we should train ourselves to *notice differently*; that is, to make sense of and attend to the multi-layered and polyphonic character of living systems. Similarly, Haraway (2008, 2016) proposes an anthropological shift that would explicitly recognise the entanglement of species, reject human exceptionalism and foster alternative practices of world-building, a notion that has resonated with scholars across various design and HCI disciplines, inspiring posthumanism, human-decentred and more-than-human approaches (i.e., Coulton & Lindley, 2019; DiSalvo et al., 2010; Forlano, 2016; Frauenberger, 2020; Giaccardi & Redström, 2020; Smith et al., 2017; Wakkary, 2021). These perspectives intentionally blur the boundaries between humans and other living entities, highlight the multiplicity and connectivity inherent in living systems and emphasise the need to foster reciprocal interactions through design.

## Multispecies Interactions in Design and HCI

Simply put, people, plants, microorganisms, animals and other entities rarely exist or live in isolation, as the many advantages of co-habitation and co-existence have been observed and confirmed over time. In recent years, the potential benefits of designing with and for multispecies interactions have been increasingly explored within the design and HCI fields, with various attempts being made to integrate the multiple, entangled, symbiotic and more-than-human aspects of nature into design practices. Within design and sustainable HCI (e.g., DiSalvo et al., 2010; Knowles et al., 2018; and for a recent overview, McQuillan & Karana, 2023), researchers have presented and discussed designs to improve interfaces and enhance human relationships with natural environments and non-human living entities (Webber et al., 2023). Such designs span a vast range of contexts and subjects, including forests (J. Liu, et al., 2018; Rogers et al., 2004), farmland (Liu et al., 2019), animals (Mancini, 2013), insects (Ikeya et al., 2023), plants (Chang et al., 2022) and gardens (Rodgers et al., 2019; Rosen et al., 2022), as well as the realm of microbes (Armstrong, 2022; Ofer & Alistar, 2023) and human microbiomes (Bell et al., 2023; El Asmar, 2019). The diversity and variety in the scale of habitats, along with the multiplicity of species that reside within them, have provided a rich backdrop for much of this research.

Digital technology is commonly integrated into efforts to establish interfaces between humans and non-human entities (Giaccardi & Redström, 2020) such as soil microbiomes (e.g., Kuznetsov et al., 2013; J. Liu et al., 2018; Rogers et al., 2004). For instance, wearable devices that detect moisture favourable for fungal activity (J. Liu et al., 2018) and digital actuators that achieve audio-visual translations of natural phenomena (Rogers et al., 2004) have been developed. Although such devices may involve multispecies interactions, they often fail to adequately consider the living consortia as part of the designed outcome. Consequently, they miss the opportunity to leverage the inherent capacity of living systems to enhance both understanding and design in the context of multispecies interactions.

In the following sections, we focus our attention on the emerging field of biological HCI, which has started to integrate living organisms into its research. This focus provides important background information for our study and highlights a relatively underexplored design space.

### *Biological HCI*

Within the emerging field of biological HCI (Pataranutaporn et al., 2020)—a growing community within HCI that explores biology as design material (Pataranutaporn et al., 2020)—a noticeable increase in the number of HCI-related publications have acknowledged and integrated the *livingness* of non-human living organisms in interaction design. Notable works in this field include interactive public art installations (Alistar & Pevere, 2020; Lee et al., 2020; Lee et al., 2015), hybrid bio-digital games (Kim et al., 2018; Lam et al., 2019; Lam et al., 2020), bio-fabrications (Lazaro Vasquez et al., 2020; Vasquez & Vega, 2019; Weiler et al., 2019), educational tools (Fein et al., 2020; Hamidi & Baljko, 2014; Risseeuw et al., 2023), microbe-integrated wearables (Ng, 2017; Vasquez & Vega, 2019), living interfaces (Barati et al., 2021; Groutars & Risseeuw et al., 2022; Merritt et al., 2020; Zhou et al., 2023) and self-trackers (Boer et al., 2020), to name just a few within this continuously growing body of work.

Within biological HCI, several theoretical frameworks have been proposed to help designers better understand and explore the material and interactive qualities of living organisms. For example, Living Media Interfaces (LMI) (Merritt et al., 2020) characterises interactions between humans and living media with a focus on those that implicate digital systems, while Living Bits (Pataranutaporn et al., 2020) conceptualises microorganisms as living computers, creating opportunities to explore new design spaces for interaction design. To address the temporalities, scales and semantics unique to microbes, Kim et al. (2023) proposed six design strategies to enhance their noticeability to the human senses, increasing understanding and empathy towards microbial worlds. With a particular focus on the physical nature of such interactions, Ofer et al. (2021) explored the direct interactions between humans and light-generating bioluminescent algae, while Barati et al. (2021) designed a DIY shaker device to investigate the various ways humans can interact with algae via kinetic stimuli. These recent works among many others in microbe-HCI (Kim et al., 2023) frame different aspects of human interaction with non-human living entities, whether to address the implications of digital and computing technologies, microbial constraints or the physical and direct nature of such interactions.

Nevertheless, there remains an opportunity to explore a framework that specifically addresses the multiplicity of interacting non-human agents to foster a more holistic and ecologically aligned approach to designing multispecies interactions. In the following subsection, we discuss the living artefacts framework proposed by Karana et al. (2020) as a foundation upon which our own proposed framework for multispecies interactions can be built.

### *Living Artefacts Framework*

Highlighting the importance of understanding *livingness* as a biological, social and ecological phenomenon in the design of artefacts, Karana et al. (2020) introduced the living artefacts framework, which extends the livingness of non-human organisms over their use time and entails three fundamental pillars: Living Aesthetics, Mutualistic Care, and Habitabilities.

*Living Aesthetics* acknowledges the temporalities inherent in biological processes of change and seeks to foster a deeper understanding and appreciation of the diverse temporalities and aesthetics associated with non-human entities. *Mutualistic Care* emphasises the importance of reciprocal and evolving relationships between humans and non-human organisms within living artefacts, recognising the interdependence that exists within these ecosystems. This principle encourages designers to consider how humans can help living artefacts thrive while also receiving functional benefits in return. Lastly, the principle of *Habitabilities* encourages designers of living artefacts to cultivate an awareness of and sensitivity to relational and connected elements within habitats, including and beyond living artefacts, by understanding the survival needs of the organisms involved. These three principles provide a framework for exploring how humans can experience and attend to living artefacts in everyday life, promoting reciprocal human-non-human interactions and sensibilities that support non-human living aesthetics and needs to enhance mutualistic care and cohabitation. In this paper, we build upon this framework and further consider how living artefacts can be integrated into the everyday life of humans as well as within non-human contexts to facilitate interactions among multiple species.

## Summary of Accounts

Based on various accounts drawn from research in the fields of design, HCI, biology and ecology, we understand *multispecies interactions* as a quality inherent and essential to healthy living systems. To further characterise this quality, we identify three key aspects of multispecies interactions: **multiplicity**, **connectivity**, and **reciprocity**.

- Multiplicity refers to the number and taxonomic diversity of species involved in an interaction, as described in research on species co-habitation and biodiversity (e.g., Bonfante & Anca, 2009; Frauenberger, 2020; Schwartz et al., 2000; Smith et al., 2017).
- Connectivity relates to the occurrence and extent of interactions between different species, which may vary depending on the degree of directness in these interactions (e.g. Ofer et al., 2021; Risseeuw et al., 2024; Zhou et al., 2023). In this context, the definition of what constitutes an interaction varies considerably across domains, such as whether one is discussing ecological interactions (Doolittle & Booth, 2017) or human-computer interactions (Hornbæk & Oulasvirta, 2017). In the following sections, we will elaborate on and clarify the concept of connectivity as it is used within different contexts.
- Reciprocity describes the practice of exchange to achieve mutual benefits (Chen et al., 2021; Estes et al., 2013; Lu & Lopes, 2022). This concept is crucial in the design of living artefacts, as exemplified by the *mutualistic care* concept (Karana et al., 2020), where mutualistic care represents a form of reciprocity between humans and living artefacts. In this paper, we seek to explore various forms of reciprocity that occur during interactions among multiple species.

We propose that these three aspects, which are vital for the collaborative survival and diversity of species in ecological systems (Forlano, 2016; J. Liu, et al., 2018; Schwartz et al., 2000), could also serve to guide designers as they explore and design for interactions within and through living artefacts and with nature at large.

Furthermore, we define multispecies interactions as the intricate interplay involving at least two species, encompassing both humans and non-humans (i.e., multiplicity), with varying degrees of connectivity and reciprocity. Using this definition and the aspects of multiplicity, connectivity and reciprocity described above, we conducted an in-depth analysis of various living artefacts, allowing us to examine and identify specific dimensions related to these three aspects and revealing the diverse ways multispecies interactions can occur within the context of living artefacts. This process is explained in further detail below and is followed by a discussion of our findings and implications for the design and HCI communities.

## Methodology

### Selection of Living Artefacts

To identify and analyse living artefacts that facilitate interactions between different species, we conducted a multi-phase systematic example collection and screening process across design and HCI venues. In Phase 1, we collected 122 examples of living artefacts. In Phase 2, we refined this collection by critically evaluating the role that multispecies interactions played in each example, leading to the exclusion of 110 examples deemed to have roles too similar to those in the final selection. This process yielded a final selection of 12 examples to represent the diverse range of methods and techniques employed by designers of living artefacts to facilitate multispecies interactions. Figure 1 outlines each phase in detail.

### *Phase 1: Collection*

The first author conducted a comprehensive collection of living artefact examples from scientific literature, design books, design blogs and portfolio websites between September 2023 and December 2023. Portfolio websites were identified by searching for the works of biodesigners who designed living artefacts. In five instances, this led to the discovery of one or more novel examples of living artefacts, which were also included. Table 1 lists the search terms used, sources and number of living artefacts collected from each source. In total, 237 examples were collected, including 80 duplicates that appeared in multiple sources which were subsequently removed, resulting in 157 unique examples. We then assessed the remaining examples to ensure that each involved a physical living artefact inhabited by actual living organisms, allowing us to provide an account of the interactions between different species. Consequently, 35 conceptual projects that did not meet this criterion were excluded, resulting in an initial selection of 122 living artefacts.

### *Phase 2: Refinement*

In this phase, we refined our collection by excluding living artefacts that were conceptually similar in terms of multispecies interactions. This was achieved as follows:

- 94 examples involved a single non-human species (e.g., a monoculture of bacteria) interacting with humans. We selected one of the more recent cases introduced in HCI, Flavorium (Groutars & Risseeuw et al., 2022), as a representative case due to 1) clear descriptions regarding the organisms implicated and 2) the fact that the artefact design was published in multiple reputable HCI venues (Groutars & Risseeuw et al., 2022; Kim et al., 2023; Risseeuw et al., 2023). The remaining 93 examples were excluded.

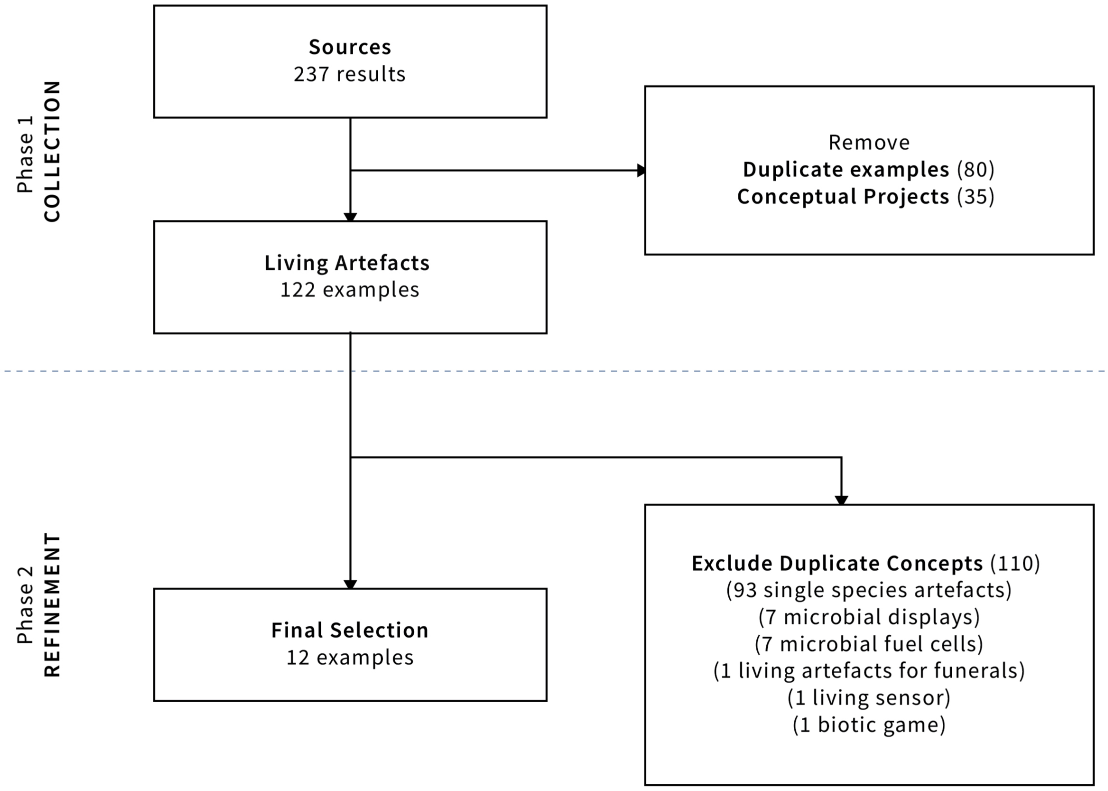


**Figure 1. Schematic overview of the example collection and refinement phases.**

**Table 1. Search terms used, source types, sources and number of examples resulting from each source.**

| Search terms | Source type | Source | Results (*n*) |
|---|---|---|---|
| Alive, living, bio, biodesign, bioart, biological, symbiosis, bacteria, bacterial, fungi, fungal, mycelium, mushroom, algae, spirulina, plant, cyanobacteria, microbial, microbes, microorganism | Online libraries | ACM library, https://dl.acm.org/ | 44 |
| | Review papers | Karana et al., 2020 | 13 |
| | | Pataranutaporn et al., 2020 | 17 |
| | | Zhou et al., 2023 | 9 |
| | | Kim et al., 2023 | 44 |
| | Books | Myers, 2014 | 29 |
| | Design blogs | http://www.designboom.com | 30 |
| | | http://www.dezeen.com | 16 |
| | | http://www.futurematerialsbank.com | 11 |
| | | http://www.materialdistrict.com | 16 |
| | Portfolio sites | http://www.ivanhenriques.com | 1 |
| | | http://www.mathieulehanneur.fr | 2 |
| | | http://www.michaelsedbon.com | 1 |
| | | http://www.novainnova.com | 2 |
| | | http://www.teresavandongen.com | 2 |

- Eight examples were classified as microbial displays. These examples featured a diverse set of organisms cultivated in a closed environment (e.g., a Petri dish) for human viewing. Of these, the most well-known example, Contagion (Takasaki & D'souza, 2011), was retained, while the remaining seven examples were excluded.
- Eight examples consisted of microbial fuel cells (MFCs), in which electrons secreted by microbes are used to power an electrical circuit (i.e., using sensors and LEDs) (Rahimnejad et al., 2015). Of these, we kept the most recent and well-known example, Electric Life (Van Dongen, 2019). The remaining seven examples were excluded. It should be noted that four other examples (Armstrong et al., 2021; Henriques, 2016; Van Oers & Nova Innova, 2023; Van Oers & Plant-E, 2016) involving MFC technology were retained due to their role in multispecies interactions beyond those taking place within the MFCs themselves.
- Two examples involved living artefacts for funerals and were comprised of a coffin and urn made of living mycelium to facilitate the process of decomposition and reuptake into nature. We retained the more widely known of these, the coffin, named Living Cocoon (Loop Biotech, 2023). The urn was excluded.
- Two examples were classified as living sensors. These featured multiple genetically engineered microbes designed to detect the presence of specific chemicals. Of these, we retained Living Tattoo (X. Liu et al., 2018) for the clarity it provides regarding the role of the organisms involved. The other example was excluded.
- Two examples were biotic game designs, in which humans interact with various organisms through a digital system. Mould Rush (Kim et al., 2018), widely known and discussed in HCI, was retained, while the other design was excluded.

This refinement process resulted in a final selection of 12 representative cases, as highlighted in Table 2 below.

**Table 2. An overview of 12 selected examples for further analysis.**

| Description | Organisms involved | Source |
|---|---|---|
| **A.L.I.C.E.** by Armstrong, Ieropoulos and Freeman, is a 'living' installation that communicates with microbes in real-time by monitoring their electricity production, allowing humans to respond to them by feeding them with our liquid waste. | 4-chamber Microbial Fuel Cells (MFCs).<br>Organism composition unclear. | http://www.alice-interface.eu |
| **Caravel** by Ivan Henriques is a self-sustaining environmental robot that cleans water by propelling itself on the water's surface. | Bacterial Colonies consisting mainly of Aerobacter species.<br>Water plants (*Pistia*). Water microbiome. | http://www.ivanhenriques.com/works/caravel/ |
| **Contagion Advertisement** by Mike Takasaki and Glen D'souza is a bacterial billboard, prepared to advertise Steven Soderbergh's 2011 film Contagion. | Various species of microorganisms applied by the designers and originating from the surrounding air. | https://www.zdnet.com/article/microbial-marketing-bacteria-and-fungi-infect-contagions-billboard/ |
| **Electric Life** by Teresa van Dongen is an art installation containing microbial fuel cells (MFCs) that power LEDs. | Various species of microbes found in the mud of rivers and lakes. | https://www.teresavandongen.com/Electric-Life |
| **Flavorium** by Groutars & Risseeuw et al. is a Living Colour Interface that displays the living aesthetics of iridescent Flavobacteria. | Flavobacteria (*Cellulophaga lytica*). | https://doi.org/10.1145/3491102.3517713 |
| **Living Cocoon** by Loop Biotech is a functional living coffin made from living mycelium that, after burial, will facilitate and stimulate the process of decomposition. | 'Local' mycelium-forming fungi.<br>Soil microbiome. | https://loop-biotech.com/living-cocoon/ |
| **Living Light** by Ermi van Oers and Plant-e is a self-sustaining lamp that harvests energy through the photosynthetic processes of plants and the metabolism of bacteria. | Exoelectrogenic Bacteria.<br>Plant (*Asparagus*).<br>Soil microbiome. | https://livinglight.info/technology/ |
| **Living Tattoo** by X. Liu, et al. is a 3D-printed living tattoo that detects chemicals on human skin. | Bacteria (*Escherichia coli*, genetically modified). | https://doi.org/10.1002/adma.201704821 |
| **Mould Rush** by Kim et al. is an online game that allows players to interact with a growing community of microbes on a plate. | Various species of airborne bacteria and fungi. | https://doi.org/10.1145/3235765.3235798 |
| **Nukabot** by Chen et al. is an intermediary digital system connecting humans to the fermenting microbes of nukadoko. | Various species of microbes. Rice bran bacteria. Lactic acid bacteria. Yeasts. | https://doi.org/10.1145/3411763.3451605 |
| **POND** by Ermi van Oers and Nova Innova is a floating network that harvests its energy from microbes and collects and communicates data about the quality of the water. | Various species of microbes found in a pond. | https://www.novainnova.com/pond/ |
| **Urban Reef** by Pierre Oskam & Max Latour is a parametrically designed and 3D-printed habitat that encourages the growth and diversity of multiple species in urban settings. | Printing paste containing different compositions of nutrients, plant seeds and mycelium spores. | https://www.urbanreef.nl/ |

### Analysis

The collected examples represented a range of disciplines and featured variations in terms of their design processes, the types of organisms involved, and their intended functionality. To compare the multispecies interactions within this diverse collection, the examples were analysed using *interaction webs*. These are based on food webs, which are commonly used frameworks in ecology to represent the relationships among species in an ecosystem (Layman et al., 2015). Essentially, interaction webs are visual representations of the multispecies interactions that occur between humans and non-human entities both within and outside of an artefact. The webs used in this study were developed by the first author and were based on interpretations of the available information about the 12 selected examples (Table 2). Examples of interaction webs generated for Flavorium (Groutars & Risseeuw et al., 2022) and Living Light (Van Oers & Plant-E, 2016) are shown in Figure 2.

By visualising the interactions between different species and the non-living components (e.g., sensors and LEDs) involved in the functioning of a living artefact, we obtained an overview of the multiplicity of these interactions. Regarding connectivity, significant variation was observed among the examples, reflecting different patterns of interaction. Lines were used to illustrate connectivity between species or non-biological actors in the interaction webs; however, these lines do not indicate the *degree* of connectivity or how it relates to reciprocity. These nuances will be discussed in greater detail in the following section.

## Results

### Three Types of Multispecies Interactions

Through the development of interaction webs, we realised that multispecies interactions take place not only **within** the boundaries of living artefacts but also **across** these boundaries.

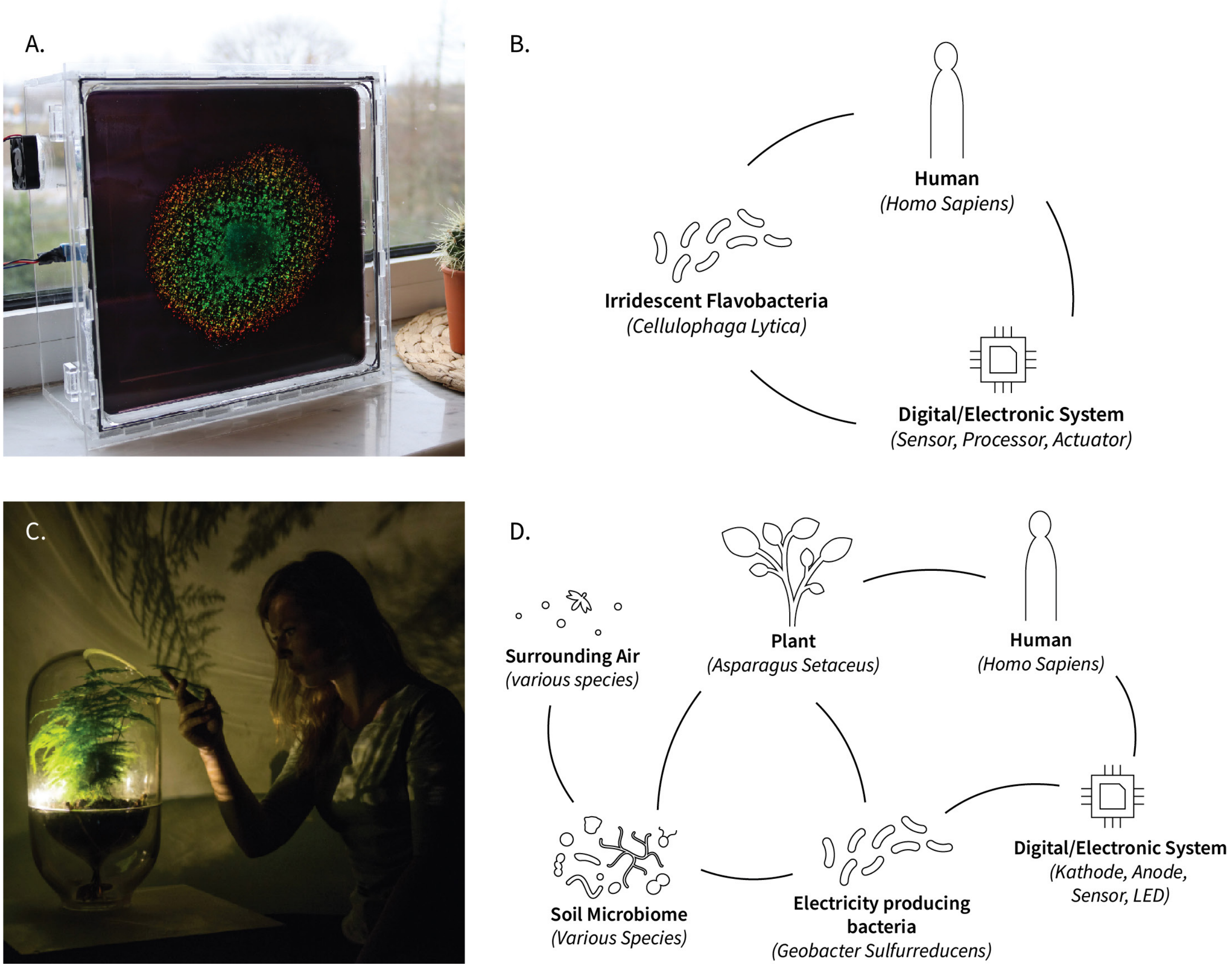


**Figure 2. Living artefacts and their corresponding interaction webs:**
A. Image of Flavorium (Groutars & Risseeuw et al., 2022) with B. visual interpretation of multispecies interactions involved in Flavorium; C. Image of Living Light lamp (Van Oers & Plant-E, 2016) with D. visual interpretation of multispecies interactions involved in Living Light.

Moreover, these interactions occur between the living artefact and its respective environment and can be further distinguished based on whether they involve non-humans (*across with non-humans*) or humans (*across with humans*). This line of thought led to the development of evaluation criteria for classifying three distinct, yet interlinked, **types of multispecies interactions**, as shown in Figure 3 below.

We categorised the living artefacts in our selection according to these types to highlight the disposition of the multispecies interactions occurring among them. Figure 4 provides an overview of this disposition and helps to clarify the role that artefacts play in facilitating certain types of such interactions. In the following sections, we evaluate each of these dynamics, focusing on **multiplicity, connectivity and reciprocity** as the key aspects underpinning the interactions across the featured artefacts.

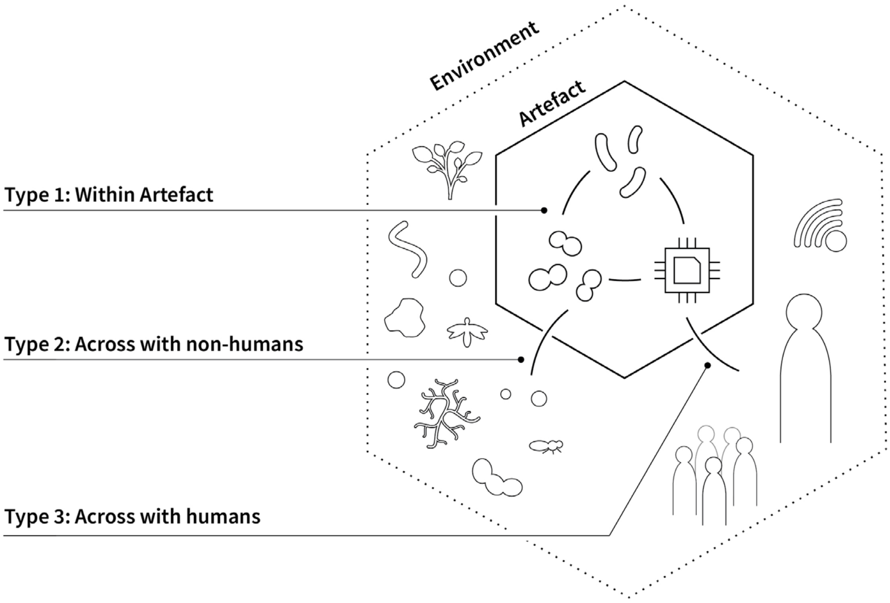
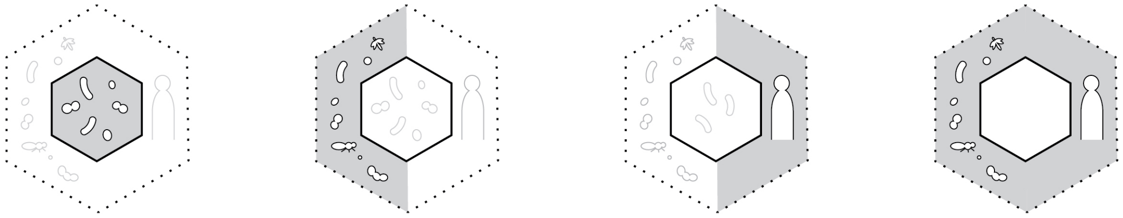


**Figure 3. Schematic representation of the multispecies interactions taking place:** within an artefact (Type 1), across with non-humans (Type 2) and across with humans (Type 3).

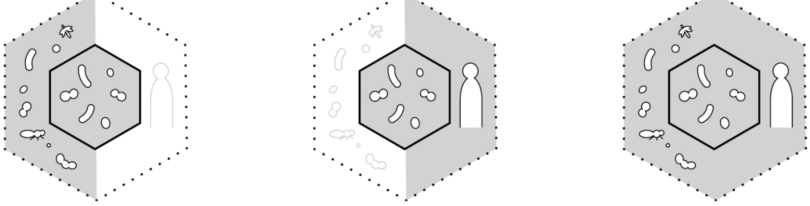


**Within**
Contagion Ad.
Electric Life

**Across with nonhumans**
Living Cocoon*
Urban Reef

**Across with humans**
Flavorium*

**Across with non-humans and Across with human**
n.a.**



**Within and Across with non-humans**
Caravel

**Within and Across with humans**
A.L.I.C.E., Living Light
Living Tattoo, Mould Rush

**Within, Across with non-humans and Across with humans**
Nukabot
POND

**Figure 4. Disposition of the different types of multispecies interactions across the different examples.**

* The examples Living Cocoon (Loop Biotech, 2023) and Flavorium (Groutars & Risseeuw et al., 2022) contain only a single species within the artefact and do not involve multispecies interactions within.

** Artefacts that facilitate only Type 2 and 3 interactions do exist; for example, in the form of tools for nature engagement (Webber et al., 2023); however, we have not yet identified any living artefacts in this category.

## Within the Artefact

This type of multispecies interaction takes place within the artefact. We differentiated artefacts based on the degree of **multiplicity** (Figure 5), which ranged from **mono-species** such as Flavorium (Groutars & Risseeuw et al., 2022) to **multispecies** artefacts like Living Tattoo (X. Liu et al., 2018). Among the multispecies artefacts, we distinguished between artefacts containing **cultivated** organisms specifically chosen by the designer and sourced from a known, pure origin (e.g., Living Tattoo and Caravel) (Henriques, 2016), and artefacts comprised of naturally occurring or **wild** assemblages of organisms that are sourced from nature and inherently consist of multiple species, the identities of which are not always known [e.g., Contagion (Takasaki & D'souza, 2011) and Electric Life (Van Dongen, 2019)]. The degree of multiplicity in wild assemblages is often accompanied by corresponding levels of **connectivity** and **reciprocity**. Conversely, some artefacts such as Living Tattoo and Caravel feature segregated species that prevent interactions between them. Below, we examine three artefacts that exemplify this variation to better understand these aspects and their intricate relationships.

Living Tattoo (X. Liu et al., 2018) (Figure 6) contains different strains of genetically engineered *Escherichia Coli* 'programmed' to act as living sensors. Although these strains are not in direct physical contact with each other, the presence of distinct, multiple strains allows for the detection of several chemicals. This example illustrates how designers can integrate multiple species (high multiplicity) while keeping them segregated (low connectivity) to attain functional versatility.

Living Light (Van Oers & Plant-E, 2016) (Figure 7) demonstrates both multiplicity and connectivity through its integration of a plant and various types of microbes. The plant produces organic compounds via photosynthesis that are then metabolised by soil microbes, establishing a reciprocal relationship between them. The soil microbes include multiple naturally occurring species, as well as *Geobacter sulfurreducens*, which was specially cultivated by the designers to produce the electrons that power the digital system. Hence, Living Light features a multiplicity of human-cultivated and naturally occurring species, with the connectivity between these species being crucial for the artefact's ability to generate light (its functionality). Furthermore, the reciprocal interactions between the plant and the soil microbes enable the self-regulation of the living artefact, so long as light and water are provided. Thus, Living Light exemplifies high-multiplicity, high-connectivity and high-reciprocity multispecies interactions.

Contagion (Takasaki & D'souza, 2011) (Figure 8) features a variety of species intentionally added by the designers in addition to contaminants from the surrounding air that colonised the artefact during its production. Contagion thus contains cultivated organisms of known origin along with naturally occurring or wild organisms of unknown origin, all of which were grown in the same habitat. During its use time, when the artefact was publicly displayed, organisms competed with one another for limited nutrients, resulting in a diverse array of growth patterns, colours and textures. In this example, the designers allowed for a high degree of multiplicity and connectivity but a low degree of reciprocity to attain a specific type of emergent and wild living aesthetics.

It can thus be confirmed that multispecies interactions within living artefacts vary in degrees of multiplicity, connectivity and reciprocity. In the following sections, we will elaborate on how these interactions can extend beyond the boundaries of the artefacts themselves.

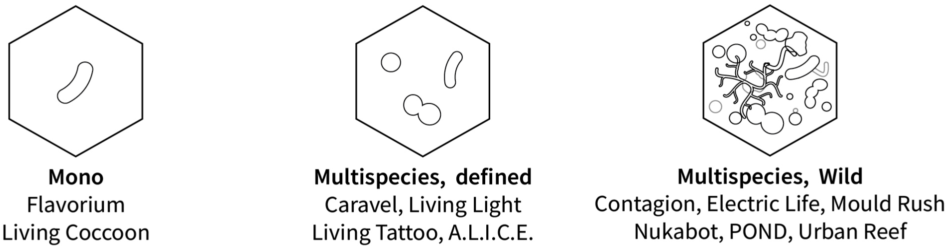


**Figure 5. Schematic representation of the variation in multiplicity among the different examples.**

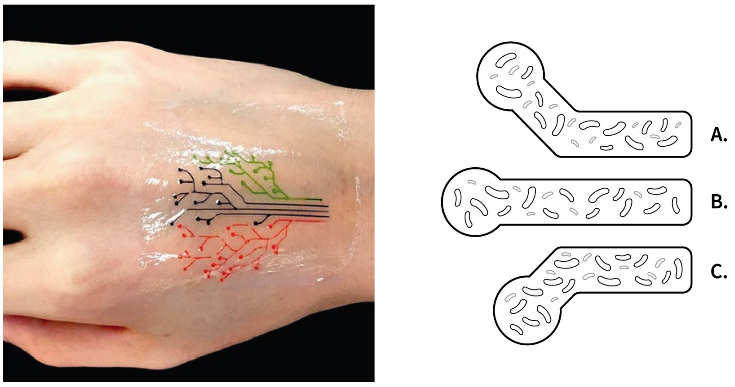


**Figure 6. Image of Living Tattoo** (X. Liu et al., 2018) (left) **and a visual interpretation of multispecies interactions within** (right); A. *E. Coli* strain 1; B. *E. Coli* strain 2; C. *E. Coli* strain 3.

**Figure 7. Image of Living Light lamp** (Van Oers & Plant-E, 2016) (left) **and a visual interpretation of multispecies interactions within** (right); A. Plant (asparagus); B. Soil microbes (various species); C. Electron-producing bacteria (*Geobacter sulfurreducens*); D. Digital system (cathode, anode, sensor, processor, LED).

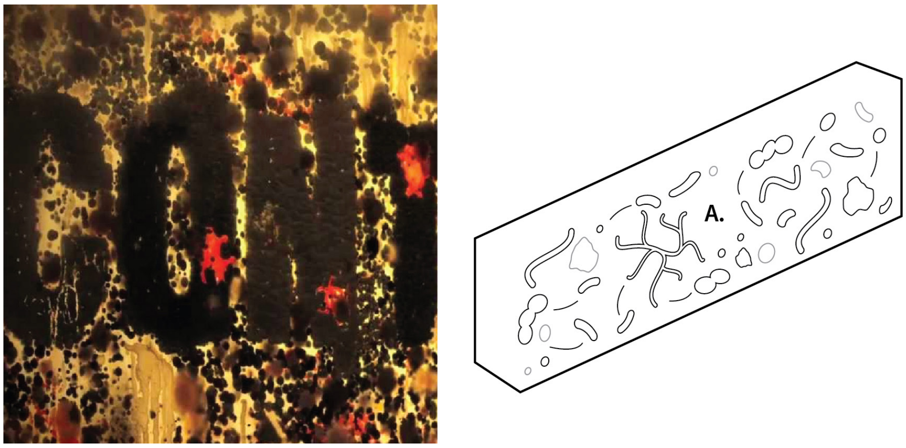


**Figure 8. Image of Contagion** (Takasaki & D'souza, 2011) (left) **and a visual interpretation of multispecies interactions within** (right); A. An assemblage of microbes (various species) in competition.

## Across the Artefact with Non-Humans

The environment surrounding living artefacts, whether human-made or natural, inherently contains a high **multiplicity** of species and interactions among them. Bearing this in mind, in our set of examples, we identified varying degrees of **connectivity** between the artefacts and their surrounding environments (Figure 9), which were particularly affected by the degree of openness of the artefact's designed habitat. Living artefacts can be categorised as **closed**, where organisms within the artefact are unable to interact beyond the artefact's boundaries during use time; or **semi-open**, where organisms within can exchange nutrients, chemical signals or electrons with non-humans across the artefact's boundaries. Although such exchanges occur between living organisms, they might not involve the living organisms themselves moving across the boundary of an artefact (hence, they are referred to as 'semi-open living artefacts'). We differentiate such semi-open artefacts from **open** ones, where living organisms are able to migrate across the boundaries of the artefact. Furthermore, in the open artefacts, we observed differences in the direction in which organisms migrate, which may be **inwards**, **outwards** or going **both ways**, the latter indicating potential **reciprocity** between species, artefacts and their environment.

In the following paragraphs, we will examine three specific examples of living artefacts that demonstrate these variations in openness and direction in light of these factors' relationship with connectivity and reciprocity.

Caravel (Henriques, 2016) (Figure 10) facilitates a type of interaction between the artefact and its surrounding environment through a semi-open design. In this system, bacteria and plants within the artefact metabolise organic compounds identified as pollutants from the surrounding water. The electron-producing *Geobacter* bacteria subsequently power an electric circuit which stores electricity, enabling Caravel to move and harvest even more organic compounds as part of a 'swarm system'. The designer created a semi-open artefact from which the organisms cannot leave, yet which allows them to interact with other species in their environment. In addition, this connectivity between Caravel and its environment is highly reciprocal; Caravel cleans its environment while harvesting energy from it for its survival.

Urban Reef (Oskam & Latour, 2021) (Figure 11) is an open artefact designed to allow for a variety of organisms to colonise it during its use time. The designers can also tune the habitabilities of the artefact to invite specific species to inhabit it. Over time, these colonising organisms interact with surrounding ecosystems in reciprocal ways, such as by providing shelter to other organisms or improving the air quality. The high degree of openness encourages inward migration, resulting in high multiplicity within the artefact and high connectivity and reciprocity across the artefact.

Living Cocoon (Loop Biotech, 2023) (Figure 12), another open living artefact, is designed to be composted, with the artefact's embedded fungal species actively contributing to the decomposition process. In terms of connectivity, nutrients are exchanged between the artefact and the surrounding soil biome, and organisms can migrate across the artefact's boundaries in both directions. During the decomposition process, the boundaries of the artefact dissolve, and the organisms once contained within it become part of the surrounding soil microbiome, demonstrating Living Cocoon's reciprocal relationship with the surrounding environment.

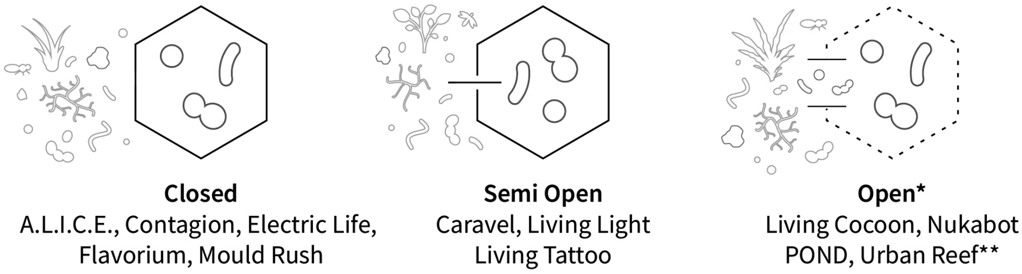


**Figure 9. Schematic representation of the examples' variation in openness, across the artefact with non-humans.**

* Open artefacts are signified by dotted lines.

** Urban Reef (Oskam & Latour, 2021) is characterised by inward migration, in contrast to the other open artefacts in which bidirectional (going both ways) migration was observed.

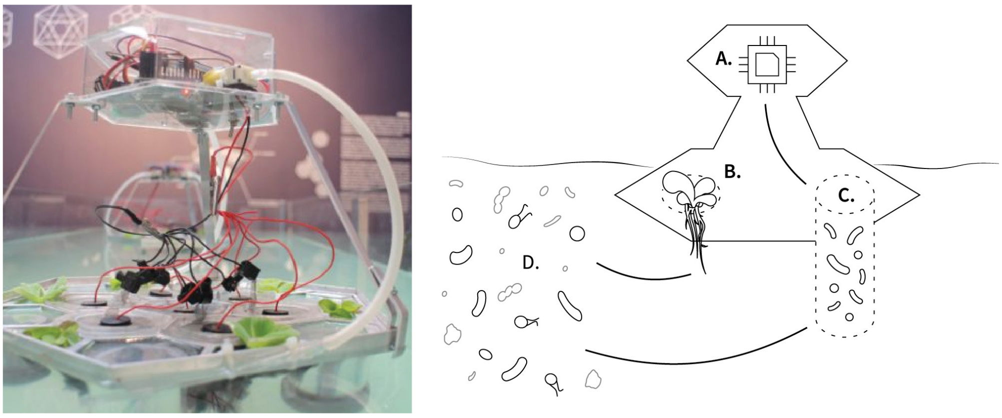


**Figure 10. Image of Caravel** (Henriques, 2016) (left) **and a visual interpretation of multispecies interactions across with non-humans** (right); A. Digital control system; B. *Pistia* water plant; C. Microbial fuel cell containing mainly *Geobacter* species; D. Surrounding water microbiome.

**Figure 11. Image of Urban Reef** (Oskam & Latour, 2021) (left) **and a visual interpretation of multispecies interactions across with non-humans** (right); A. Organisms in the surrounding ecosystem; B. Organisms initially inhabiting the artefact.

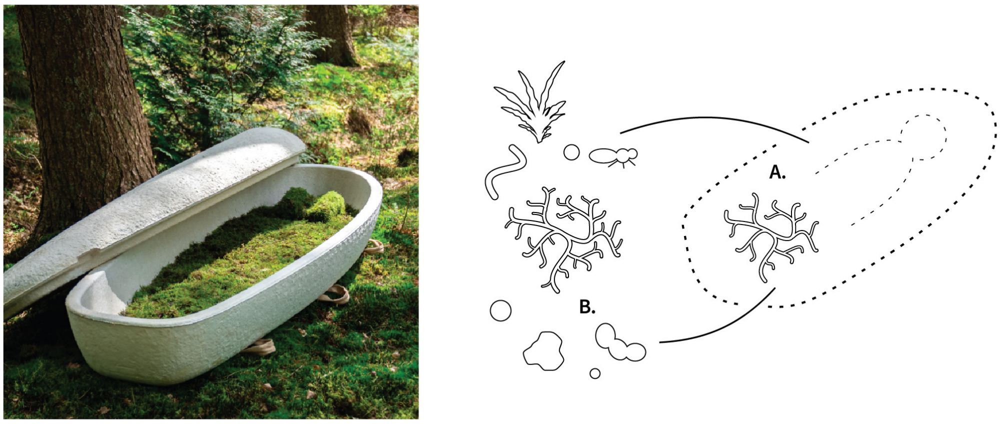


**Figure 12. Image of Living Cocoon** (Loop Biotech, 2023) (left) **and a visual interpretation of multispecies interactions across with non-humans** (right); A. Coffin comprised of local fungus; B. Surrounding soil microbiome.

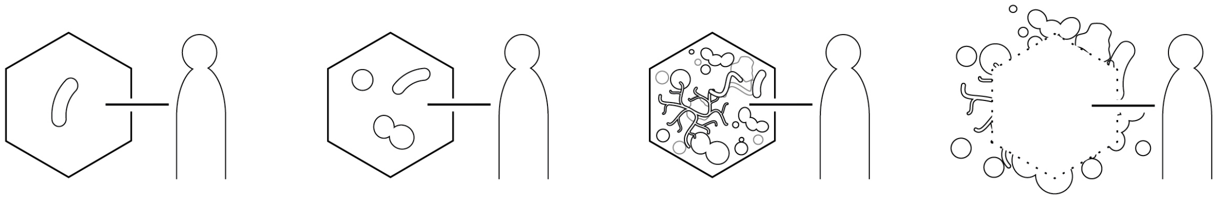
## Across the Artefact with Humans

During our examination of interactions across living artefacts with humans, variations in **multiplicity** were immediately apparent. Humans can interact with artefacts that host a single species, multiple species, wild assemblages or even entire ecosystems (Figure 13). Simultaneously, such interactions can occur with a single human, as seen in Living Tattoo (X. Liu et al., 2018), or multiple humans, as in the case of Mould Rush (Kim et al., 2018). Regarding **connectivity**, interactions with humans are often mediated by digital technology, exemplified by living artefacts like A.L.I.C.E. (Armstrong et al., 2021).

Within these examples, we identified the **directness** of interaction, defined as the closing of the temporal gap between an input and an output of an interactive system (Rasmussen et al., 2012; Zhou et al., 2023), as a key dimension of variety for distinguishing diverse degrees of connectivity and **reciprocity** between humans and non-humans. Additionally, our analysis revealed multiple examples in which the directness of the interactions took on a distinct, ecologically defined form. For example, in A.L.I.C.E., liquid waste produced by humans serves as a food source for the organisms within the artefact, representing a form of ecological reciprocity (Douglas, 2021). This brought us to the notion of *ecological interactions* (Estes et al., 2013), which we will explore further in relation to the directness dimension through three illustrative cases.

In the biotic game Mould Rush (Kim et al., 2018) (Figure 14), multiple humans interact in an online environment with an assemblage of microorganisms contained within the artefact. This multiplicity of both humans and non-humans generates a novel and emergent gameplay experience. Through digital augmentation, human players experience a direct interaction with the living artefact as their in-game actions generate direct feedback from the living organisms. However, since the living organisms are contained in a sterile environment, there is no direct interaction, in an ecological sense, with the human players.

In Nukabot (Chen et al., 2021) (Figure 15), humans (as well as the user's skin microbiome) interact with a complex assemblage of rice bran bacteria incubating within a wooden casket to co-create fermented vegetables. Human users care for Nukabot and receive feedback through a digital system regarding the well-being of the microbes. This digital system translates the high degree of multiplicity and reciprocity into signals that are comprehensible to the human user, who receives implicit feedback on the quality of the care they are providing (indirect interaction). Additionally, humans consume the vegetables along with the organisms that fermented



**Single species - Humans**
Flavorium

**Multiple species - Humans**
A.L.I.C.E.
Living Light
Living Tattoo

**Wild assemblage - Humans**
Mould Rush
Nukabot

**Ecosystem - Humans**
POND

**Figure 13. Schematic representation of the examples' variation in multiplicity, across the artefact with humans.**
Five examples (Caravel, Contagion, Electric Life, Living Cocoon and Urban Reef) were excluded from this analysis due to insufficient evidence of clear interactions between humans and the living artefacts as described.

them. The assimilation of these organisms into the human gut microbiome provides an additional example of the ecological interaction taking place between artefact and human.

POND (Van Oers & Nova Innova, 2023) (Figure 16) is a living artefact that is integrated into its surrounding ecosystem. At the bottom of natural bodies of water, debris, organic matter and microbes decompose it, generating an electric potential. This potential is harnessed by POND's electronic circuit to monitor and communicate information about water quality and the well-being of the ecosystem to human viewers. Since humans have the potential to impact this ecosystem, the interaction may be considered implicit or indirect. What is unique is that POND provides an opportunity to interact with an entire ecosystem rather than just an isolated community or specific type of organism. Through such a reciprocal interaction, the designers aimed at *surfacing the livingness* of the ecosystem.

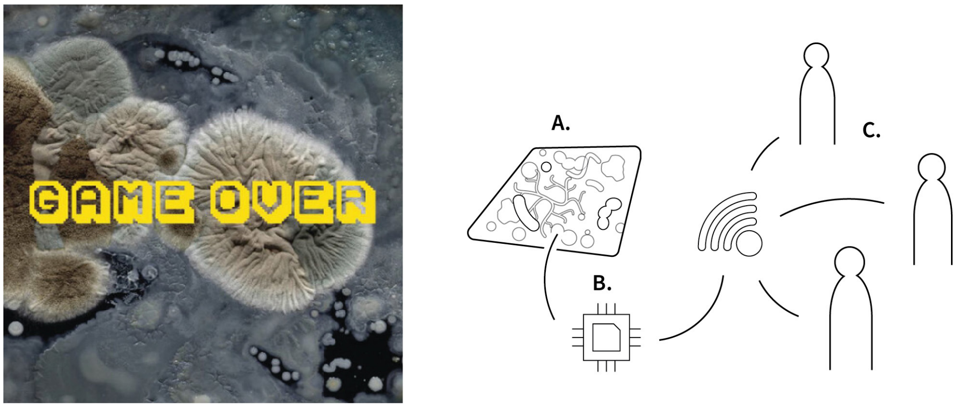


**Figure 14. Image of Mould Rush** (iKim et al., 2018) (left) **and a visual interpretation of multispecies interactions across with humans** (right); A. Assemblage of organisms (various species); B. Electronic circuit (sensors, processor, actuators); C. Multiple human players interacting with the system via the internet.

**Figure 15. Image of Nukabot** (Chen et al., 2021) (left) **and a visual interpretation of multispecies interactions across with humans** (right): A. Assemblage of organisms (various species); B. Electronic circuit (sensors, processor, speaker, actuator); C. Human user; D; Gut microbiome of the human.

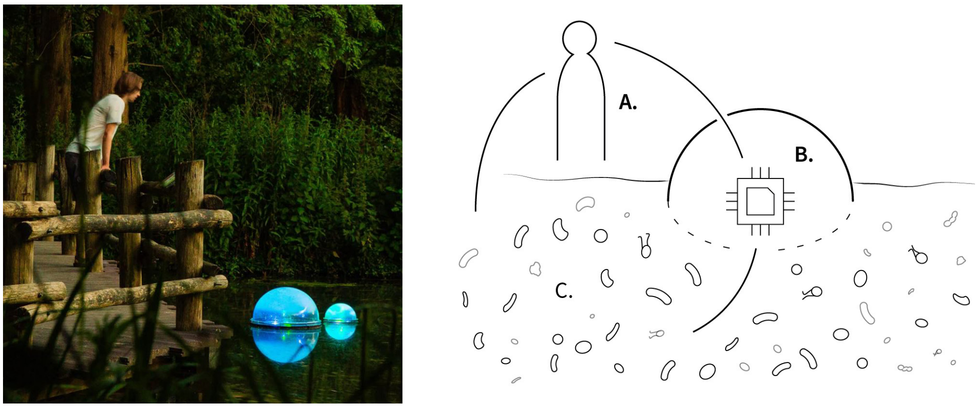


**Figure 16. Image of POND** (Van Oers & Nova Innova, 2023) (left) **and a visual interpretation of multispecies interactions across with humans** (right); A. Human; B. Electric circuit (cathode, anode, sensors, processor, LED); C. Surrounding aquatic biome.

## Discussion

Living artefacts that facilitate and leverage interactions among diverse species hold the potential to interface the daily lives of humans with their ecological surroundings. This paper seeks to provide guidance to prospective designers for unlocking this potential. Based on the aspects of multiplicity, connectivity and reciprocity inherent to multispecies interactions, we analysed how designers have integrated multispecies interactions into their work. We visualised these efforts using interaction webs and proposed three distinct yet interlinked types of multispecies interactions that can enhance the future design of living artefacts for multispecies interactions. In this section, we will revisit the typology and discuss its implications as an emerging design space for biodesign and HCI.

### Potentials of Multispecies Interactions for Design

#### *Multispecies Interactions for Functional Versatility*

From a functional perspective, the involvement of multiple agents offered a greater degree of versatility in each of the multispecies interactions we explored, from the co-creation of complex flavour profiles in fermented foods enabled by Nukabot (Chen et al., 2021) to the self-sufficient power generation of Caravel (Henriques, 2016). Our collection of living artefact examples demonstrates how high multiplicity leads to functionally versatile outcomes that would not be possible within mono-species systems. Furthermore, advancements in technologies such as gene editing (e.g., Zhang et al., 2019) and *engineered living materials* (Gilbert et al., 2021; Nguyen et al., 2018) suggest that the functional versatility of multispecies approaches can be further enhanced. Ongoing projects at the intersection of synthetic biology and design demonstrate this potential. One such project is NextSkins (Karana, Ellis et al., 2023), which develops living therapeutic materials for restoring skin microbiome health, achieving a high level of precision across a diverse range of functionalities through the deployment of various engineered organisms. While such rapidly evolving technologies hold promise for exciting and novel applications based on the capabilities of interlinked living systems, they also raise significant ethical concerns, which will be discussed in the section below addressing dilemmas and challenges.

#### *Multispecies Interactions for Ecological Living Aesthetics*

Multispecies interactions can enrich aesthetic experiences in ways that might not be possible with mono- or single-species interactions. Throughout this paper, we analysed in detail how intricate living aesthetics (i.e., the way we experience the biological changes of living artefacts over time) (Karana et al., 2020) could be leveraged and enhanced in the context of three types of multispecies interactions. For example, Contagion (Takasaki & D'souza, 2011) showcased a captivating microbial display with rich colour and texture resulting from the competition among multiple fungal and bacterial species. The designers intentionally facilitated serendipitous interactions between these species to enhance living aesthetics.

With interaction types 2 and 3, where (semi)open containments enable organisms to cross between different habitats, greater connectivity provides designers with additional opportunities to explore the potential of living aesthetics. This high level of connectivity in multispecies interactions allows for a broader range of type, degree and duration of biological change, resulting in living aesthetics that emerge from the combined efforts of the non-human and human actors involved. These emergent and unpredictable living aesthetics, driven by the intricate relationships among living species within an ecosystem, are referred to as *ecological aesthetics* (Erzen, 2005) and present opportunities for a greater appreciation of natural systems as well as the integration of non-anthropocentric and regenerative design paradigms (Wahl, 2016). Here, bringing about the cultivation of such ecological aesthetics through living artefacts could prove to be a valuable pathway to enhance reciprocity and mutualistic care between humans and non-humans.

#### *Multispecies Interactions for Regenerative Ecologies*

Our analysis demonstrates that living organisms interacting across the boundaries of an artefact can contribute to exchanges across multiple environments. For instance, by fertilising surrounding soils, as in the case of Living Cocoon (Loop Biotech, 2023), or removing pollutants from water [Caravel; (Henriques, 2016)]. This *regenerative potential* of living artefacts (Karana, McQuillan et al., 2023) is heightened when multiplicity, connectivity and reciprocity are carefully considered and integrated into design decisions.

Herein, the optimal degree of openness (i.e., connectivity) in the artefact design and the provision of a suitable habitat that allows organisms to migrate between the artefact and its surrounding ecosystem [i.e., *habitabilities*; (Karana et al., 2020)] play a crucial role. This is exemplified by Urban Reef (Oskam & Latour, 2021), where habitabilities are tuned to stimulate inward migration and promote biodiversity in urban environments, and POND (Van Oers & Nova Innova, 2023), where the organisms that enable the artefact's functionality are those found in its immediate environment. These artefacts become integrated with their respective ecosystems, partaking in local cycles and blurring the boundaries between artefacts and ecosystems. Such high degrees of connectivity imply that living artefacts can function as interfaces between humans and ecosystems, offering new opportunities for *noticing* and mutualistic care (Karana et al., 2020) while aligning with broader discussions that challenge the traditional boundaries between humans, nature and technology (e.g., Coulton & Lindley, 2019; Forlano, 2016; Giaccardi & Redström, 2020; Wakkary, 2021). As awareness and a commitment to sustainable design and ecological awareness grow (McQuillan & Karana, 2023), designers are presented with an unprecedented opportunity to promote the potential of living artefacts to seamlessly transpose between both the social and ecological realms.

Unravelling the design potential of multispecies interactions within and across living artefacts entails complicated technical, methodological, sociocultural and ethical challenges, among others (Forlano, 2016; Karana, McQuillan et al., 2023). Designers seeking to create artefacts that facilitate interactions among multiple species must cultivate a specific mindset and approach to effectively address the challenges they will face. In the following section, we will briefly expound upon some of these key challenges and considerations.

## Challenges and Dilemmas of Designing for Multispecies Interactions

### Ethical Concerns Surrounding Biodesign

As discussed in the prior section on *regenerative ecologies* (Karana, Mcquillan et al., 2023), biodesign has the potential to solve various social and environmental challenges. However, it is crucial to assess the broader implications of such solutions and recognise the systemic changes required to achieve holistic sustainability (Ginsberg & Chieza, 2018). For example, Asveld et al. (2019) propose that the concepts *risk management* (i.e., what risks genetically modified organisms in everyday artefacts pose to humans and natural ecosystems) and *economic justice* (i.e., the economic impacts of biotechnological solutions for all stakeholders involved, such as farmers of genetically modified crops) should be considered in all biotechnology endeavours to support the acceptability and progress of biotechnology as a whole.

Within the context of biodesign, ethical considerations are discussed more broadly by incorporating the presence and agency of other living organisms. This approach recommends developing sensibilities to the unique temporalities, scales and needs of organisms, and adjusting the role of the biodesigner accordingly (Ikeya et al., 2023; Karana, McQuillan et al., 2023; Ofer & Alistar, 2023; Zhou et al., 2023). Armstrong (2022) emphasises that:

> “decentering the human from sole authorship of biodesign practice requires a more inclusive and distributed approach to design practice, as the biodesigner becomes part of an expanded community of multi-species participants, radically altering how biodesign is imagined, executed, and sustained.” (p. 14)

In conclusion, biodesign—particularly the design of living artefacts—holds significant promise for the development of regenerative ecologies rooted in the inherent capabilities of biology. However, actions in this field must be taken with a deep sense of responsibility for social and environmental sustainability, with designers exercising care and sensitivity towards all living beings with whom we share our world. Designing for multispecies interactions entails similar commitments, but the higher multiplicity of species and a greater degree of connectivity among them adds further complexity, necessitating even greater prudence. We will further elaborate on some of these aspects below.

### Embracing Emergence and Unpredictability

Throughout the history of interaction design and HCI, there have been persistent efforts to engineer predictability within interactions (Dabrowski & Munson, 2011). Since the industrial revolution began, designers have strived to create interactive systems powered by machines with predictable response times and outputs to enhance efficiency and productivity. Even in biological HCI, a relatively recent field that frames living organisms as part of such machinery, various quantitative analyses have been conducted (e.g., Barati et al., 2021; Groutars & Risseeuw et al., 2022) with the intention to characterise and engineer measured, predictable outcomes in human-biology interactions. That said, given the increasing number of discourses that demonstrate the potential advantages of working with (and not against) more-than-human perspectives, such as those from bio-art (Myers, 2015) and HCI (e.g., Giaccardi & Redström, 2020; Wakkary, 2021), we propose that designers adopt an alternative mindset and approach that embraces the emergent aspects of nature, especially its unpredictability. This perspective has been broadly discussed in the context of material-driven design in a recent CHI article (McQuillan & Karana, 2023), suggesting its potential for creative and divergent design outcomes. Beyond the benefits that come with adopting an open mindset that embraces emergence and unpredictability, designers must still navigate the additional challenges of encountering and reconciling potentially conflicting values of the various human, non-human and technological agents involved in multispecies interactions.

### Collaborating with vs. Controlling Living Systems

Through our research, we identified diverse interpretations regarding nature and its role in the context of working with living organisms. One interpretation views humans as collaborators with natural living systems (Collet, 2017; Karana et al., 2018), embracing their complexity and emergent properties. Another perspective sees humans as controlling and simplifying these living systems in order to operationalise them. Designers must decide how much control to exert when engaging with multispecies interactions, navigating the design space based on their particular goals. As shown throughout our analysis, such considerations and actions are closely related to the degree of multiplicity and connectivity. While some designers may opt to embed a cultivated, single-species community [e.g., in Flavorium (Groutars & Risseeuw et al., 2022)], others integrate an entangled assemblage [e.g., in Electric Life (Van Dongen, 2019)]. The cultivated organisms in Flavorium are selected by humans and are of known origin; in contrast, Electric Life features living assemblages sourced from nature and contains a multitude of organisms that often cannot be precisely identified. In addition, designers can decide whether to allow various organisms to migrate across an artefact’s boundaries, increasing multiplicity while reducing control, as seen in Urban Reef (Oskam & Latour, 2021).

While an open and collaborative approach to nature appears favourable from the perspectives discussed earlier, a cultivated and isolated set of organisms—or organisms that are genetically engineered for a specific purpose—can be highly beneficial for the mass production of food or medicine and often requires less energy and resources compared to conventional means (Gavrilescu & Chisti, 2005; Nguyen et al., 2018). Therefore, designs implicating different types of multispecies interactions require careful negotiation, where designers must strike a harmonious balance between exercising control to shape multispecies interactions and fostering collaboration that leverages the versatility and resilience inherent in multispecies systems. Within this delicate interplay, functional and sustainable benefits can emerge that honour the needs of both the human and non-human organisms involved.

### *Safety Concerns*

Designing for multispecies interactions poses significant challenges for maintaining biological harmony and ensuring appropriate levels of safety for the collaborators involved in living artefacts. This is particularly challenging due to additional complexity and the possibility of unintended outcomes arising from the multiplicity of interactions among interlinked species. Designers must recognise that natural living systems are complex and not fully understood. Well-intentioned efforts to improve or harmonise an ecosystem—such as the introduction of new species into a habitat—can have catastrophic effects, as observed in previous case studies in which the intentional release of invasive species caused unintended harm (Andersen et al., 2004; Mooney & Cleland, 2001; Sakai et al., 2001). To mitigate such risks, we recommend that designers collaborate across disciplines and work closely with experts in ecology and biology to make informed decisions when attempting to integrate and manage multiple and potentially invasive species in their designs.

## Reflections and Future Work

In this paper, we advocate for an ecological approach to designing living artefacts for multispecies interactions. To better understand how these interactions are currently integrated into living artefact designs, it was necessary to simplify certain aspects, such as delineating between diverse species and distinguishing between humans and non-humans. While this process may seem at odds with non-anthropocentric ideas of *noticing differently* (Lowenhaupt Tsing, 2015) and the *rejection of human exceptionalism* (Haraway, 2016), we recognise that these ideas are central to the values underpinning our research. Nevertheless, we found it necessary to make these simplifications and distinctions to present multispecies interactions as a workable concept for design and HCI. Moreover, we distinguished between non-humans and humans to better identify relationships and make them more actionable for prospective designers working in this context. This distinction also helped to highlight that living artefacts are often still conceived and designed with human-centred functionality in mind, revealing new possibilities for future design endeavours involving humans and other living entities.

We introduced interaction webs to provide a simplified visual aid to help designers comprehend the interlinked and multilayered relationships within living systems. While this approach may be considered somewhat reductionist, categorising and simplifying living systems is a common practice in ecology (e.g., Doolittle & Booth, 2017; Layman et al., 2015; Lenat & Resh, 2001). Furthermore, the goal was not to reduce complex systems into mere components but rather to enhance understanding of the various inter-relationships and underlying principles that govern living systems. However, we acknowledge that our analysis and the accompanying interaction webs are far from complete. For that matter, it is likely that the use of living artefacts leads to additional multispecies interactions not originally intended by the designers. Moreover, data regarding the species involved and how they relate to one another was not always publicly available for every example we presented. Moving forward, we propose that longitudinal studies be combined with emerging technologies to facilitate deeper investigations, offering new directions for future research. This approach can provide further insights into the long-term implications of multispecies interactions while offering new technical tools and more comprehensive frameworks for prospective designers and researchers.

### *Expanding the Scope of Interaction in Design*

Throughout our research, we found it challenging to answer our own internal critical line of inquiry; that is, defining precisely what is meant by interactions, and what their constituents should be in this context. In contrast to the traditional dyadic interaction paradigm used to explore relationships between humans and machines, our domain extends beyond the human-computer interface to encompass ecological interactions. This expanded design space introduces a multitude of new variables, including a diversity of non-human temporal scales, variable response times, concealed and intangible interaction dynamics and additional outcomes that may transpire beyond the threshold of human perception. Therefore, our research seeks to broaden the scope of interaction in design and realise a more nuanced understanding of interactions from an ecological standpoint. To achieve this would open up avenues for broader exploration within design and HCI, particularly in specialised areas such as human-plant interaction (Chang et al., 2022), animal-computer interaction (Mancini, 2013) and human-nature engagement (Webber et al., 2023). Identifying and evaluating multispecies interactions across these domains will not only highlight their presence and reveal their potential for enabling regenerative ecologies but also help to further refine multispecies interactions as a workable design concept.

# Conclusion

This paper introduced an ecological approach to design with a specific focus on leveraging living artefacts to foster interactions among multiple species. By drawing upon insights from ecology, design theory and HCI literature and conducting a thorough analysis of various living artefacts, we identified and developed three essential dimensions for assessing these interactions: multiplicity, connectivity and reciprocity. Furthermore, we classified multispecies interactions into three distinct types: those occurring within artefacts; interactions between artefacts and non-human entities; and interactions involving living artefacts and humans. Our analysis provides a nuanced understanding of the dynamic interplay among different species and reveals the rich spectrum of multispecies interactions facilitated by living artefacts. Given the inherent complexity of these interactions, it is imperative to adopt an ecological approach that properly accounts for and thoroughly examines each component within a living system and the relationships that occur among them. This approach is not only fundamental for discerning and interpreting the intricate dynamics at play within ecological systems but is vital for the design of living artefacts that can be seamlessly integrated into both social and ecological contexts.

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