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Becoming microbes: An approach to cultivating microbial sensibilities in biodesign

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Abstract: Microbes assume an indispensable role in design, given their inherent adaptability, functional diversity, and abundance. Yet, designing with microbes presents notable challenges for biodesigners, stemming from, for example, the distinct temporalities and scales of microbes. Conversely, cultivating microbial sensibilities—reflecting human comprehension and alignment with the distinctive characteristics of microbes—stands out as a unique potential of biodesign for fostering a deep connection between humans and other living entities. In response, we present the concept of "becoming microbes", a philosophically grounded approach advocating for a non-anthropocentric stance in biodesign, aiming at immersing biodesigners in the realms of microbes with a fresh perspective for imagining the world through the lens of a microbe. By harnessing diverse microbial qualities, including motility and communication, we present various design avenues to explore the notion of becoming microbes. We reflect on the role of merging the biological with the immersive digital systems in this context.

Keywords: biodesign; more-than-human; microorganisms; becoming

1. Introduction

Biodesigners act at the intersection of biology and design, incorporating living organisms into design outcomes to achieve novel functions, expressions, and sustainable solutions (Myers, 2012; Collet, 2018). Through such synthesis of new hybrid typologies, biodesign has been positioned as distinct from green design and biomimicry (Myers, 2012). For example, designers in architectural domains have explored methods for transforming living cells into materials, mainly focused on microorganisms (e.g., mycelium) coupled with digital technologies to shape the concept of *living construction*, such as grown, self-healing buildings (Dade-Robertson, 2020). In product design, Camere and Karana (2017) studied the fabrication of materials from living organisms, emphasising the potential for enhanced sustainability, production efficiency, and collaborative design possibilities utilising the unique characteristics of growing microbes, especially fungi, bacteria, and algae. In more recent developments, Karana et al. (2023) expanded on the concept of *living artefacts* (Karana et al., 2020), which integrates biodesign with living organisms to foster new functionalities and interactions in daily life. The latest approach aligned living artefacts with sustainability discussions and more-than-human ontologies, offering promise for regenerative ecologies characterised by mutualism and coevolution (Karana et al., 2023). To aid designers in unleashing the potential of living artefacts, the authors outlined five essential principles, complemented by guiding inquiries and illustrative cases.

As interest in biodesign increases and tools and methods from biology and life science have become more accessible to designers, exploration of technologies for interaction with living organisms has naturally advanced. In particular, the Human-Computer Interaction (HCI) domain has been actively exploring the application of technology in biodesign, with a notable increase and diversification of works in the last ten years (Kim et al., 2023). Thus, many scholars have formed the Biological-HCI (so-called Bio-HCI (Pataranutaporn et al., 2018)) and Microbe-HCI (Kim et al., 2021) communities through various research over the past decade. For instance, the works *Human-Biology Interaction* (HBI (Lee et al., 2015)), *Human-Microbe-Interactive* (HMI (Lam et al., 2019)), *Living Bits* (Pataranutaporn et al., 2020), and *Living media interfaces* (LMIs (Merritt et al., 2020)) have provided new design frameworks and space for new ways for interactive systems by including microorganisms as interfaces. Practical applications have been introduced, including living colour interfaces with flavobacteria (as shown in Figure 1 (Groutars & Risseeuw et al., 2022)), living light interfaces with bioluminescent algae (Barati et al., 2021; Ofer et al., 2021), and living chromic interfaces with cyanobacteria (Zhou et al., 2023).

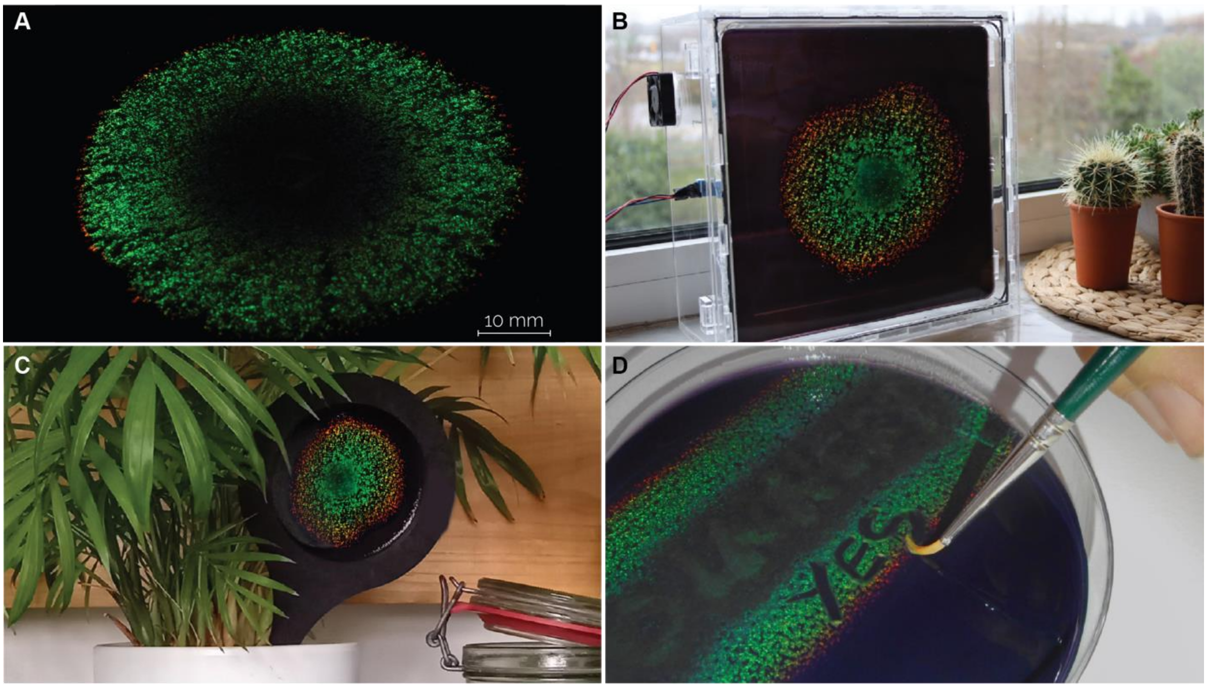

Figure 1 Flavobacteria's structural colour (A), Application directions: Living monitor (B), Living label (C), Living notes (D) (Adapted from Groutars & Risseeuw et al., 2022).

Microorganisms, such as mycelium, bacteria, yeast, and algae, have played an essential role in the growth of biodesign. They have not only produced unique examples but also facilitated the scaling-up and commercialisation of biomaterials (D'Olivo & Karana, 2021). Simultaneously, engagement with microorganisms has accentuated designers the importance of connectivity with ecosystems and the surrounding environment. Since microbes contribute to nearly every natural cycle, upholding the existence of higher trophic lifeforms and influencing global climate conditions (Cavicchioli et al., 2019), they have also been profoundly shaping human interactions and experiences with the world. This interdependence urges biodesigners to enhance their comprehension of microorganisms and responsibly manage to work with the so-called "invisible majority" (Kim et al., 2023, p.1). Consequently, microorganisms in biodesign not only underscore their utilitarian significance as novel materials but also the intrinsic value of non-human entities, i.e., *more-than-human*.

This paper makes a contribution to the emerging field of biodesign by proposing a design strategy to overcome unique challenges, such as spatiotemporal qualities and ethical considerations, that integrating microbes brings into design. To address this challenge, we introduce the concept of "becoming microbes," a philosophically grounded approach aimed at fostering a deeper understanding and connection with the microbial world. We reflect on the potential of merging biological and immersive digital systems in this context. This contribution enhances our understanding of the role of microbes in contemporary biodesign practice.

2. Biodesign and More-than-human

In contemporary academia, the advent of *more-than-human* perspectives and discourse (e.g., (Abram, 1997; Barad, 2007; Despret, 2016; Haraway,1987; Ingold, 2000; Latour, 1987; Tsing, 2015; Stengers, 2015)) signifies a pivotal shift. These perspectives challenge anthropocentrism, revealing the intricate interplay between humans and non-human entities and setting the stage for a broader exploration of these ideas within various academic domains. In design research, more-than-human discourse also expands beyond traditional user-centric approaches to acknowledge the interplay between humans, technology, and the broader ecosystem. It emphasises ethical, ecological, and material considerations, recognising non-human entities' agency and promoting ecosystem-centred design for more inclusive, sustainable, and ethical solutions (Giaccardi, 2020; Wood, 2022). Building from such discourse, designers continue to contribute through myriad ways in embedding more-than-human design thinking, i.e., a paradigm that stimulates design practices for impact beyond humans, with particular consideration of the agency and performances of other living and non-living things (including AI technologies) (Clarke et al., 2019; Coulton & Lindley, 2019; DiSalvo & Lukens, 2011; Forlano, 2017; Giaccardi & Redström, 2020; Wakkary, 2021). In terms of considering living non-human entities - in particular microbes - researchers such as those from Human-Computer Interaction (HCI), have also sought more-than-human approaches in their works. For instance, Kim et al.

(2023) developed a taxonomy of surfacing *livingness* (an inherent material quality of living artefacts) in microbial displays. Whilst the taxonomy offered designers structured lenses with which designers can better notice living microorganisms, it also considered microbial welfare and the promotion of mutually beneficial relationships between humans and microbes by ordering the different levels of surfacing lenses according to their non-anthropocentric essences. Meanwhile, *Cyano-chromic Interfaces* by Zhou et al. (2023) presented a way to align temporal dissonances between humans and photosynthetic cyanobacteria.

In terms of non-living probes, in 2018, Liu et al. designed interactive artefacts to foster human-nature connectedness for designers. The authors demonstrated the possibility of extending bodily sensations into the environment by prototyping wearable devices to interact with mycelium in order to orient post-anthropocentric design. Similarly, to help biodesigners understand microbe requirements better, Ofer and Alistar (2023) developed "sensory engagement probes" to interact with bacterial cellulose during its growth. The abovementioned scholars commonly argue that there is a need to develop new non-human sensibilities in designing with living organisms. Still, there is a gap in culturing these more-than-human sensibilities in biodesign.

This research, positioned at the intersection of biodesign and more-than-human, begins by examining the gaps left by existing sensitisation endeavours from earlier studies. Focusing on microbes, we acknowledge that designers today face formidable challenges in noticing and empathising with these organisms. Among the challenges, the diverse temporalities and scales of microbes, for example, have been discussed in prior studies as one of the biggest hurdles in biodesign (Kim et al., 2023; Zhou et al., 2023). As a proposition to start this research trajectory, this research will introduce the "becoming" practice as an approach to cultivating microbial sensibilities from a non-anthropocentric perspective.

3. Becoming: An Approach to Cultivating Microbial Sensibilities in Biodesign

3.1 Becoming and Becoming non-human

Training one's senses to understand and experience other living things, which is largely framed under the notion of becoming in philosophy and art, has long existed. The act of becoming in humanities has been in different forms and scales, ranging from simple physical simulation to more *in-situ* mindful experiences. An earlier example of being non-human like an animal goes back to 1974, with the work titled, *What is it like to be a bat*? by Thomas Nagel. In this paper, Nagel argued that no matter how highly developed a technology is, it would be difficult to imitate other species perfectly, owing to the subjectivity of an individual's experience of nature. There is an asymmetry between the first-person perspective and the third-person narrative perspective of an experience (Araújo, 2010; Nagel, 1974). This becomes evident when humans try to understand how creatures like bats, known for their echolocation skills, navigate. People can describe and imagine their methods but cannot truly grasp their unique ways of perception, movement, and existence (Araújo, 2010).

Whilst explaining the uniqueness of life experience with the term *Qualia* - a term that philosophers use to describe the nature or content of people's subjective experiences, a simple physical act of becoming does not demonstrate this gap of 'what it is like'; the character of mental states (Thomas, 2009). The following *Umwelt* concept supplements the discourse related to becoming's subjectivity along with *Qualia*. Introduced by Jakob von Uexküll (1926), *Umwelt* refers to an organism's self-centred world where it lives and perceives (Kull, 2010). According to Von Uexküll, each organism displays its own distinct ambient, with different perceptions among species resulting from their adaptation to, and existence within, ever-changing environmental conditions (Wuketits, 1984). Importantly, *Umwelt* indicates that *Qualia* can be both a structured biological function and an objective understanding of asymmetric experiences (Araújo, 2010; Von Uexküll, 2004). For example, by following other species' perceptual signal traces and building a new relational context with their *Umwelt*, people can endeavour to enter their world (Von Uexküll, 2010; Wright, 2014). In light of the *Umwelt* concept, the notion of becoming takes on a deeper dimension, emphasising the cultivation of continuous relationships that reshape one's environment through internal and external transformations. This can be done by trying to approach a shared zone of proximity between each *Umwelt* to look at the world from their perspective more than from imitation (Deleuze & Guattari, 1987; Shores, 2017).

3.2 Becoming-with

By narrowing this to more-than-human and ecological frames, becoming can be further discussed as a *becoming-with* (Haraway, 2016) concept. As Donna Haraway (2007) points out, considering interspecies relationships in becoming is more highlighted in this vast network of ecosystems, as humans are aware of the world's interconnectivity and live with various non-human domains. *Being a Beast* (Foster, 2016) serves as a thought-provoking example of immersing oneself in a shared environment with wildlife from their perspective. Foster deliberately sought to understand the sensory experiences and behaviours of badgers, otters, deer, foxes, and swifts by imitating their modes of living. This experiential learning approach allowed him to develop a deeper connection with the natural world and to explore the idea of "becoming" a part of the environment. *GoatMan* by Thomas Thwaites (2016) is another illustrative example in this context. The designer disguised himself as a goat, using an exoskeleton and prosthetic legs and attempted to live with the animals in various parts of the Alps for a few days (see Figure 2). He was able to recognise the senses and behaviours of animals that humans do not have and participate in the world in a less self-centred manner.

Figure 2 GoatMan (Thwaites, 2016, Image by Tim Bowditch).

Such transformative manners stand out in areas that interact directly with life, like biodesign. Particularly, designing artefacts that users equip in their bodies, such as garments, allows both designers and microbes to *become* new materialities that embrace the possibilities of life for design outcomes *with* growing, connecting, and making-with (Bruggeman & Toussaint, 2023). This collaborative entanglement of humans and non-humans can enhance a holistic understanding of working with living organisms and further connect each other (ibid).

3.3 Becoming Microbes

Integrating these descriptions of becoming, we propose *becoming microbes* as a philosophically grounded approach advocating for a non-anthropocentric stance in biodesign, aiming at immersing biodesigners in the realms of microbes with a fresh perspective for imagining the world through the lens of a microbe. Becoming microbes focuses on systematically supporting designers to learn and cultivate microbial sensibilities in their biodesign process. This support will bear tracking the cultivation of the sensibilities in outputs derived from biodesign processes by objectifying sensitisation experiences. To aid in the sensitisation process, we propose the use of appropriate artefacts that would simulate microorganisms or microscopic worlds, which would invite continuous immersion from the users of the artefact. Through this process, we expect designers to experience deeply intervening in the incorporated microbes' domain. We orient this form of practice towards mixed interventions led by virtual interventions in the physical environment, such as biodesign labs and workshops, as the primary application environment. Audiovisual will be the main sensorial display involved in virtual performances of becoming. Additionally, this practice may also consider olfactory, gustatory, and tactile senses when applied in physical and mixed environments. However, despite this foundational demeanour for becoming microbes, several limitations have been in methodologically constructing it to sensitise towards them.

Microorganisms are challenging to perform this becoming practice for microbial sensibilities due to their microscopic scale, invisibility, and transient nature. These microbe-specific technical challenges (Kim et al., 2023) make emphasising audiovisual elements in virtual interventions crucial. In addition, bringing smell, taste, and hearing into the physical environment in the intervention towards microorganisms is followed by practical challenges (ibid), such as biosafety regulations. Digital tools that create an immersive experience could be essential in addressing the aforementioned microbial design challenges.

4. Immersive Digital Tools: An Opportunity

Becoming microbes in the context of biodesign opens up exciting design possibilities while also presenting unique challenges. This approach allows designers to cultivate sensibilities towards microorganisms, offering a more comprehensive understanding of their behaviours and attributes. Furthermore, on a practical and technical level, digitisation of microbes from physical to virtual may help to mitigate potentially harmful or unsafe interactions between the designers and the real physical microbes of interest, as previously pointed out in prior works in biological-HCI. For instance, *Mould Rush*, a biotic game that integrated biological materials and processes into digital/video gaming platforms, addressed ethical and safety considerations by avoiding the physical risks that microbes pose to players through online interactions (Kim et al., 2018). In particular, mixed interventions using immersive digital tools can contribute to discovering biodesign areas that have not been explored due to existing microbial qualities and realising more multidimensional design possibilities.

Heightened interest in using digital tools for ecosystems and living organisms, accompanied by a concerted effort to bridge the longstanding divide between humans and the natural world throughout human history (Webber et al., 2023), has importantly led people's comprehension of the biological realm (Gilbert et al., 2012). For example, *Quantitative Colour Pattern Analysis* (QCPA), which combined calibrated digital photography with visual modelling, offered a framework for analysing diverse data on the optical perception of animals to aid in comprehending the role of colour signals in nature (Van den Berg et al., 2019). Combination with state-of-the-art technologies and biological systems have often supported the fabrication process in biodesign (Camere & Karana, 2017) and also have a potential role in promoting communication, cooperation, and affective forms of relationality between living organisms and humans (Zhou et al., 2022). These features of digital materiality are distinctly characterised by its precise programming capabilities, ability to promote networked collaborations, democratise data accessibility and shareability, automate processes, and fundamentally support the generation and distribution of complex data in biodesign. Along with these merits, utilising digital tools that facilitate immersive experiences is also promising for conducting *becoming microbes*, and for cultivating microbial sensibilities in biodesign. Immersion in design can be defined as the degree to which a user feels deeply engaged and absorbed within a digital or physical environment, fostering a heightened sense of presence and active involvement (Agrewal et al., 2020). This concept is crucial in creating compelling user experiences, as it aims to make individuals feel fully integrated and connected with the designed space or interface.

Computer-generated environments (e.g., immersive, multisensory 3D technology that can give experiences similar to being in nature) are used as a substitute for direct contact with nature, offering a simulated yet engaging experience (Webber et al., 2023). It can also create spaces to manipulate and augment real-world roles and functions that do not need to be fulfilled perfectly to reinforce them (Beira et al., 2013; Krueger, 1977). These may include recreating a particular space (e.g., *Interaction design for kid's technology-enhanced environmental education* (Dervan et al., 2008)) or creating a general natural environment (e.g., *Nature vs. Stress: Investigating the Use of Biophilia in Non-Violent Exploration Games to Reduce Stress* (Reetz et al., 2021)), which obviates time-related challenges associated with nature, allowing new ways of experiencing the temporal dimensions of the natural world. Specifically, when dealing with microorganisms, there is tremendous value in overcoming chronic spatiotemporal challenges to the microworld (i.e., temporalities and scales) via the application of computer-generated immersive environments. Immersive digital tools can freely adjust time and space beyond simulation. Since microorganisms usually exist and are observed as more than a single cell (e.g., as colonies or networks), having manipulatable spatiotemporal options will allow the perception of unimaginable scenarios and relationships.

A number of projects have used immersive digital tools to implement experiences of "becoming" other species. *PHOX Ears* (Kleinberger et al., 2015) is a head-mounted listening device that modifies the user's auditory experience based on features of desert fox ears. The idea behind this device was to enable users to perceive sound in different ways and capture distant sounds in their surroundings, similar to how a desert fox would. Many instances exist where people have explored new perspectives through the use of a head-mounted display (HMD), such as virtual reality (VR) and mixed reality (MR). In her *Frog Vision* work, Hye-Soo Yang (2014) demonstrated how frogs see the world through VR and motion capture appliances (Figure 3).

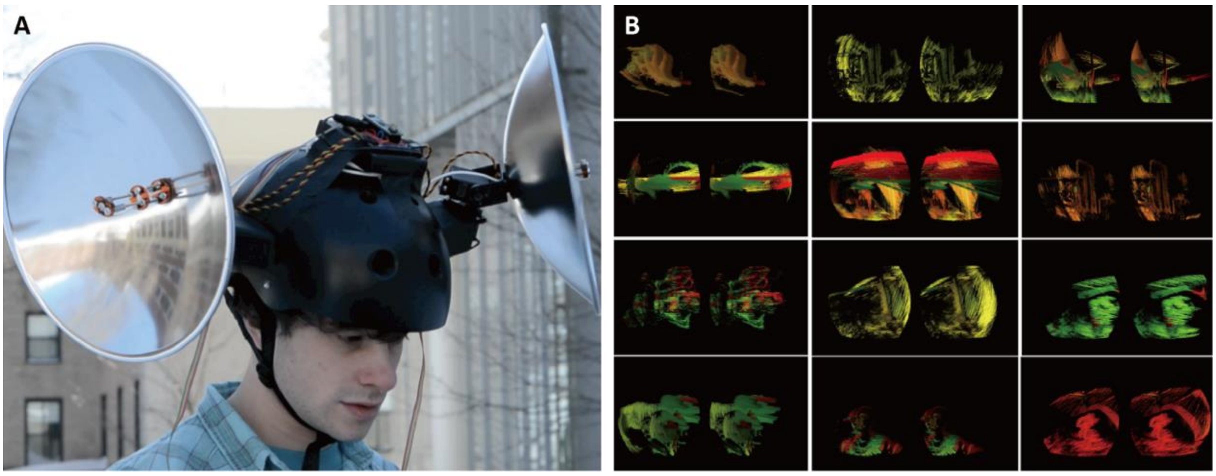

Figure 3 PHOX Ears (A) (Kleinberger et al., 2015), Screenshots of Frog Vision (B) (Yang, 2014).

Chris Woebken and Kenichi Okada have collaborated on various *Animal Superpowers* projects since 2007. One of their notable works is the *Ant Apparatus*, which aimed to replicate the vision of an ant through immersive devices. Marshmallow Laser Feast (2015), a British-based virtual reality team, introduced the *In the Eyes of the Animal* project. It provided an audiovisual experience of walking in nature through a head-mounted display (HMD) to the same forest space but as other species than humans (e.g., insects, wildlife). Plus, they helped understand dynamics that are intangible or difficult to recognise with the human eye through visual abstraction. Simone Ferracina's immersive augmented reality work *Theriomorphous Cyborg* is a game environment implemented using locative media, sensors, and portable devices. He aimed to create wearables that offer unique sensory capabilities to explore other species' *Umwelts*, opening up new perceptual realities and previously invisible worlds (Dodington, 2011; Metcalfe, 2015) (Figure 4).

Figure 4 Ant Apparatus (A) (Woebken & Okada, 2008), In the Eyes of the Animal (B) (Courtesy of Marshmallow Laser Feast, 2015, Image by Luca Marziale), Theriomorphous Cyborg: Level 1 - Magnetic vision (C) (Ferracina, 2011, as cited in Dodington, 2011).

Whilst these works do not involve microorganisms, they present an immersive experience into the world of other living beings using digital tools, striving to achieve a sense of becoming. The forms expressions in the artefacts showcased above share similarities with those designed to enhance rewilding experiences, such as *Cyborganic* (Flanagan & Frankjaer, 2018), heightening certain senses while constraining others through the use of physical probes. In a similar vein, Ahn et al. (2016) demonstrated the potential of embodied experiences to facilitate the formation of connections between humans and non-human entities through immersive simulations in which they experience their fate by becoming organisms involved in controversial circumstances in today's environmental issues.

Immersive digital tools offer an opportunity to integrate the concept of becoming microbes and nurture microbial sensibilities within the biodesign process. By creating controlled environments, these tools enable the observation of microorganisms' activities without direct physical interaction, thereby mitigating risks associated with laboratory work and ensuring ethical treatment of these organisms. Collaborative development, exploration, and experimentation become feasible through these platforms. Additionally, they facilitate the study of microorganisms' temporal and spatial dimensions, which can be challenging to achieve in the physical realm. Furthermore, virtual interventions help bridge the perceptual gap between humans and the microbial world across various scales, fostering a deeper understanding and appreciation of these essential components of ecosystems.

In summary, immersive digital tools not only offer a novel pathway for biodesign to explore the concept of becoming microbes but also address safety, practical, and ethical concerns while harnessing the advantages of digital materiality for a more comprehensive exploration of the microbial domain. Yet, how can we utilise these tools to design immersive experiences that derive inspiration from the unique qualities of microorganisms, which serve as the focal point for exploring the concept of becoming? Below, we will outline a starting point for this endeavour.

5. Design Avenues for Becoming Microbes

In this section, we introduce six design pathways aimed at delving into the concept of becoming microbes, which emerge from the diverse qualities and behaviours exhibited by microbes. We delve into the design challenges and opportunities that arise from integrating immersive digital tools into these biodesign pathways. We have designed a series of pictograms (as shown in Figure 5) to support the six outlined design pathways. Drawing from the standard safety labels in laboratory environments, we have created these pictograms to serve as creative instructional cues for designers working with microorganisms in a biodesign lab.

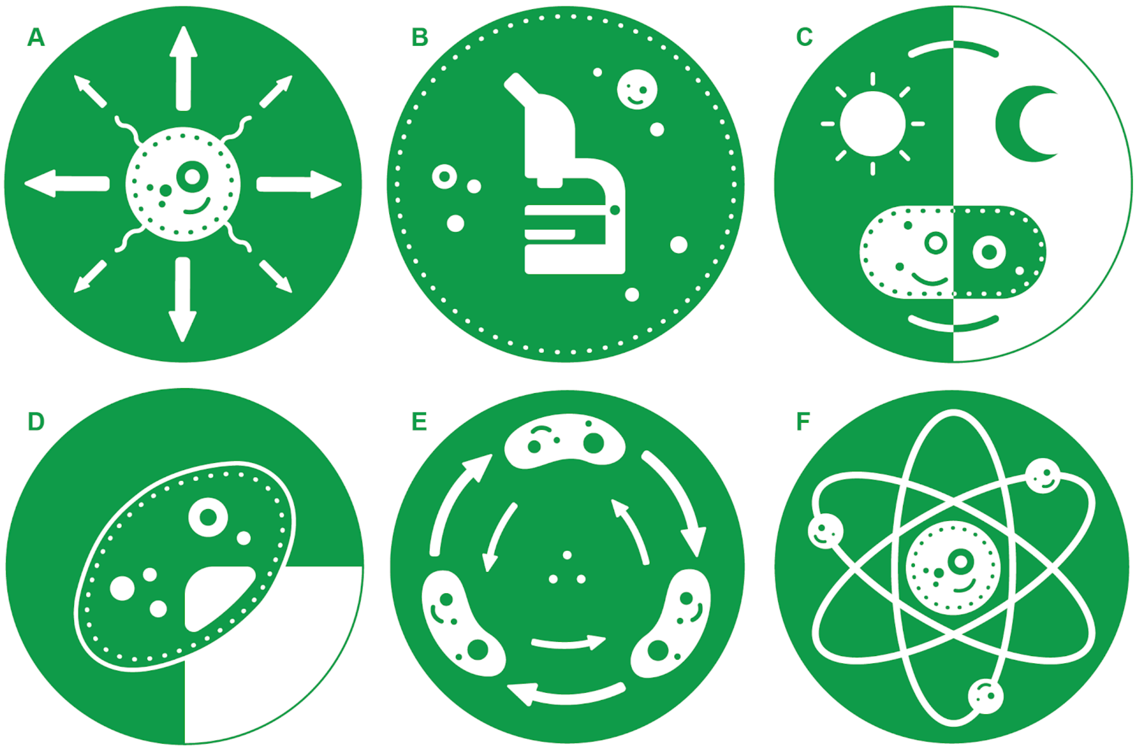

Figure 5 Microbial Motility (A), Microbial Scales (B), Microbial Rhythms (C), Microbial Translucency (D), Microbial Communication (E), Microbial Biophysics (F).

Microbial Motility. Microorganisms have different types of motility that range from very slow to rapid. Bacteria, being diminutive, use various movement strategies such as flagellation, gliding, swimming, and movement promoted by external factors like fluid flow (Madigan et al., 2019). Although this motility might seem perceived as slow by humans, it is very dynamic in the microworld, and it fits several survival purposes, such as finding nutrients, escaping predation, etc. Creating an immersive digital tool that simulates the microbial world requires capturing and representing this diverse motility accurately. It involves understanding the propulsion mechanisms and environmental cues that influence their directional navigation. By incorporating these diverse modes of movement in digital tools, biodesigners can gain a comprehensive understanding of how microbes explore and inhabit their surroundings.

Microbial Scales. The scale of microorganisms is widely acknowledged as *microscopic*, yet when contextualised within their ecological habitats, they exhibit spatially abundant distribution in all dimensions. Microbial habitats represent locales where microbes engage in resource acquisition and interaction, and their size and associated microscale processes significantly influence *macroscopic* phenomena (Smercina et al., 2021). For example, soil microbiomes exert profound results on soil health and climatic dynamics (Jansson & Hofmockel, 2020). Biodesigners can gain insights into these micro-macro scales of microbes through the utilisation of digital tools. For example, computer-generated immersive environments provide beneficial platforms for navigating the scales and distribution of microbes in an iterative (moving between scales) and relational (understanding how different scales and distributions of microbes affect microbial behaviour and responses) context. These environments afford less restrictive capabilities related to the quantification of microbial scales over time; a task that can be demanding to execute within physical settings. Furthermore, designers may conceptualise biologically hyperconnected artefacts that mirror the intricate, multi-layered features of microbial scales in their artefacts.

***Microbial Rhythms*.** Here, we propose that the digital tool could aid in the understanding of the rhythms of microorganisms, such as the circadian. Many pet owners adjust their lifestyles to accommodate their non-human companions. Similarly, microbiologists schedule their work routines to align with the biological rhythms of the microbes they study. Microbial circadian rhythms, integral to various cellular processes, can be showcased in immersive digital tools. These tools can emulate internal bacterial clocks, demonstrate how light affects the activities of certain microbes, show time-dependent variations in microbial activities, and depict responses to environmental factors that impact circadian patterns. By synchronising a researcher's cycle to microbes (i.e., temporal alignment (Zhou et al., 2023)), these tools could assist biodesigners in understanding how microbes adapt and function within a temporal framework, providing a graphic of their time-dependent requirements in different environments.

***Microbial Translucency*.** In nature, many microorganisms are difficult to detect due to their thin and translucent membranes made of materials that do not absorb light easily (Paustian, 2017), which is compounded further due to the microscopic scale of the organisms. To visualise them, researchers typically use dyes or digital image processing techniques (e.g., augmenting images captured by microscopes). Researchers also often create human-scale graphics in virtual simulations to enhance microbial visibility. However, by embracing their translucency, we can speculate complementary ways to understand what such translucency offers in the microbe realm. For example, biodesigners may consider emphasising the translucency of microbes in their visualisations instead of resorting to colouring techniques. Similar to other designs that endeavoured to picture animal vision (i.e., becoming), this can be an additional lens for scrutinising microbes. As scientists identified apochlorotic (colourless) diatoms exhibit distinct traits from photosynthetic diatoms (Lewin & Lewin, 1967), acknowledging translucency as a microbial attribute can deepen biodesigners' comprehension of its function and physiological characteristics.

***Microbial Communication*.** Intercellular signalling, which involves interactions and movement of key biochemical components on a molecular scale, is a fundamental characteristic of all cellular life in prokaryotes and eukaryotes (Lodish et al., 2008). Quorum sensing, for example, is one of the pivotal communication systems among many bacterial species, allowing them to coordinate action, especially regulating gene expression, based on population density (Madigan et al., 2019). Implementing this mechanism into digital tools will show how microbes communicate and detect under conditions to change their behaviour in response to population density changes. For instance, assuming a biodesigner using an immersive digital tool becomes cyanobacteria, the designer could act individually until enough other participants join. From the moment the quota is met, the designer should participate in and follow collective decisions about the colony. This way, we would observe how these interactions affect microbial activities, such as biofilm formation, toxic factor expression, or cooperative manners. Additionally, we could also gain a deeper understanding of how bacteria work together and function collectively on their scale.

***Microbial Biophysics*.** The microscopic world relies heavily on biophysical factors to define the unique qualities of microbes. These organisms sustain their metabolic activities by adhering to fundamental laws, which intricately shape their spatiotemporal features. One of these laws, for example, - the square-cube law - governing the changes in surface area-to-volume ratio as organisms alter in size influences microbes' performance. These laws can be incorporated into a digital tool to help designers understand how nutrients are absorbed and how Brownian motion (i.e., the unpredictable movement of microbes in fluids) affects their motility. By virtually experiencing the size of a microbe based on the square-cube law, biodesigners can envision microbes' quick movement due to their high surface area-to-volume ratio. Prioritising the biophysics of microorganisms not only enhances scientific rigour but also supports a better understanding of the intricate spatiotemporal nature of the microbial world.

Through an exploration of the six qualities and related design pathways, biodesigners can acquire valuable insights into microbes' ***living aesthetics*** (Karana et al., 2020)**,** i.e., how the changes in microbe mechanisms are manifested in the expression of living artefacts. Understanding these dynamic and temporal qualities of microbes related to these six pathways requires capturing, modelling, and simulating the behaviours of microbes in relation to diverse environmental inputs. In this context, it is essential to understand factors such as nutrient availability, temperature, pH, and other ecological parameters. By incorporating these variables into digital tools, biodesigners can witness and anticipate scenarios that affect microbial growth and behaviour. They can also grasp how these factors are shaped by human interactions and environmental conditions. For example, utilising immersive digital tools holds promise in facilitating this process by enabling navigation and transition between the scales and temporalities of both humans and microbes. For instance, Risseeuw et al. (2023) developed an interactive digital tool that enables designers to virtually inoculate bacteria and manipulate stimuli to adjust flavobacteria's colour in a digital environment. Indicating how changes in environmental conditions can impact microbial growth rates, reproduction cycles, or metabolic activities would offer insights into their unique living aesthetics.

6. Work in Progress

To illustrate the proposed design avenues, we engage in speculative discourse regarding potential biodesign scenarios utilising immersive digital tools. We begin with the motility and scales of microbes, specifically cyanobacteria, as our point of departure, exploring how these qualities can be conveyed to biodesigners within an immersive setting (refer to Figure 6 for a visual depiction of this setting). In this scenario, a biodesigner sits in an immersive room observing another biodesigner in a biolab interacting with cyanobacteria in a liquid culture.

The biodesigner in the lab stirs the flask, observing the movement of the green liquid while wearing a head-mounted display. Through this display, they zoom into the flask, witnessing the intricate movements and reorganisation of billions of cyanobacterial cells as the designer continues to interact with the flask. Concurrently, these movements and scales are translated into abstract images and projected onto the walls of the room, enabling the biodesigner to experience the distribution of microbes on a larger scale, which permeates our surroundings. Although not illustrated in this example, a conceivable scenario might involve presenting the broader ecological impact of the microbe to the biodesigners, simultaneously acquainting them with the organism's natural habitats. In this scenario, both the biodesigner in the biolab and the biodesigner who observes witness and experience the various scales and motility of microbes.

Figure 6 Visual depiction of a conceptual immersive environment enabling zooming in and out to explore the scales and motility of cyanobacteria.

It is important to note that our approach does not advocate for immersive digital tools to replace direct interactions and hands-on explorations with microbes, as suggested in recent biodesign publications aimed at enhancing humans' sensibilities towards them (e.g., Risseeuw et al. (2024), Ofer & Alistar (2023)). Instead, we believe that digital tools can effectively complement hands-on explorations, assisting biodesigners in cultivating microbial sensibilities in a more efficient, safe, and ethical manner.

7. Conclusion

This research aims to develop a novel non-anthropocentric approach to biodesign, with the goal of advancing the field towards ethical and more inclusive pathways where designers develop sensibilities towards microorganisms throughout their design processes. In pursuit of this goal, we propose the concept of "becoming microbes" as a framework to facilitate the creation of interconnected and holistic living artefacts that embrace the microbial realm. Through the utilisation of immersive digital tools, designers can further bridge the gaps between their knowledge of microorganisms and the broader ecosystem, providing opportunities for deeper exploration. We offer design pathways to explore the notion of becoming microbes by harnessing diverse microbial qualities.

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