Living Bits : Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction

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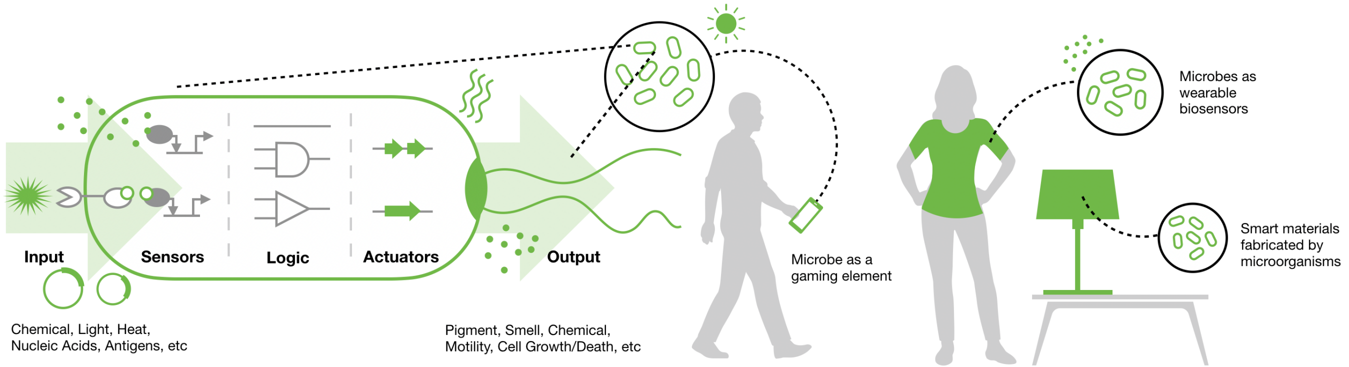

Figure 1: The microbial cell is considered a biological computer with various input and output modalities.

ABSTRACT

There are trillions of living biological "computers" on, inside, and around the human body: microbes. Microbes have the potential to enhance human-computer interaction (HCI) in entirely new ways. Advances in open-source biotechnology have already enabled designers, artists, and engineers to use microbes in redefining wearables, games, musical instruments, robots, and more. "Living Bits", inspired by Tangible Bits, is an attempt to think beyond the traditional boundaries that exist between biological cells and computers for integrating microorganism in HCI. In this work we: 1) outline and inspire the possibility for integrating organic and regenerative living systems in HCI; 2) explore and characterize human-microbe interactions across contexts and scales; 3) provide principles for stimulating discussions, presentations, and brainstorms of microbial interfaces. We aim to make Living Bits accessible to researchers across HCI, synthetic biology, biotechnology, and interaction design to explore the next generation of biological HCI.

CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**; **Interaction techniques**; **Interaction design theory, concepts and paradigms**.

KEYWORDS

Biotechnology, Biological Interfaces, Synthetic Biology, Microorganism, Living Interfaces

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1 INTRODUCTION

With the ubiquitous nature of computing, the relationship between humans and computers is becoming more intimate. In addition to wearable computers on the body, there are trillions of living "computers" on, inside, and around the human body: microbes. The term microbe or microorganism refers to micron scale $(1 \times 10^{-6} m)$ living organisms, including bacteria, yeast, and fungi. These microorganisms have been integrated with human life for thousands of years. We have used them in the form of ancient technology to create, transform, and preserve materials and chemicals such as foods and agricultural products.

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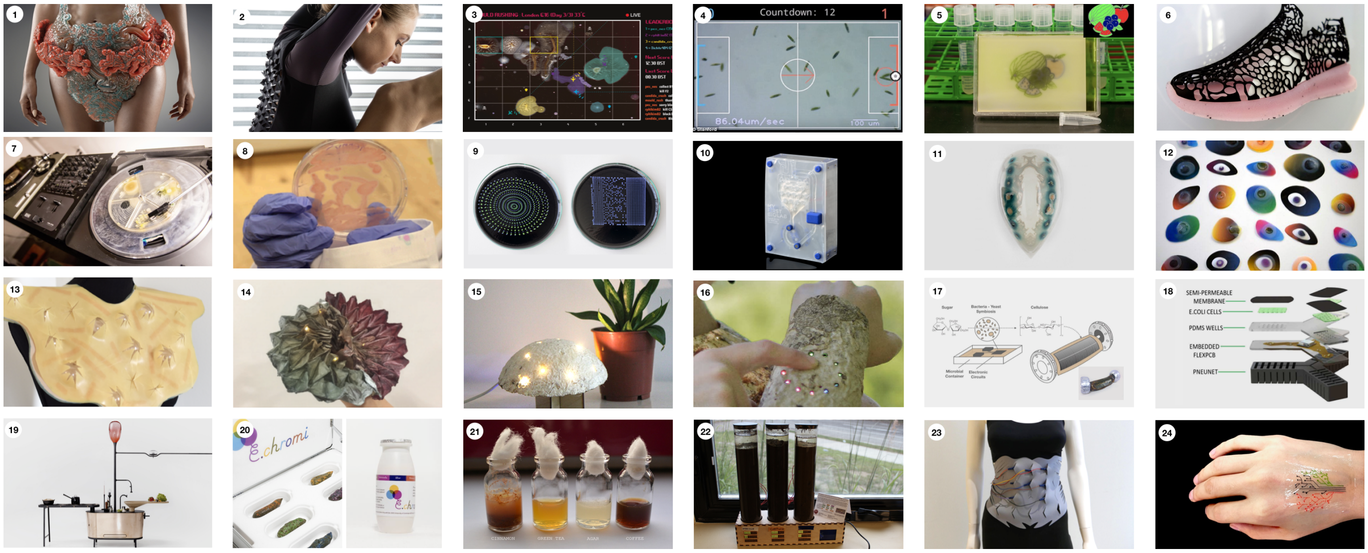

Figure 2: Projects discussed in Living Bits. 1. Mushtari [4], 2. bioLogic [73], 3. Mold Rush [34], 4. Euglena Soccer Game [31], 5. RGB E.Coli [15], 6. Breathing Shoes [40], 7. Biota Beat [35], 8. Antibiotic-Responsive Bioart [37], 9. OpenLH [23], 10. My First Biolab [22], 11. Vespers [3], 12. Carbon Eaters [40], 13. Social Microbial Prosthesis [12], 14. Grown Microbial 3D Fiber Art [48], 15. Mycelium Artifacts [71], 16.Myco-accessories [64] 17. Growable Robot [52], 18. Biosensing Soft Robot [8], 19. Microbial Home [47], 20. E. chromi [11], 21. Microbial Perfume[68], 22. Bio-electronic soil sensing device [38], 23. Gut-Brain Computer Interfaces [67], 24. 3D Printed Living Responsive Materials and Devices [45].

As Mark Weiser, pioneer in ubiquitous computing said "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it" [72]. His philosophy also applies to biotechnology, one of the oldest and impactful technologies that humans have invented.

In this paper, we introduce "Living Bits": the integration of microorganisms in, with and as computing systems. Inspired by how Tangible Bits sought to bridge the gap between the digital and physical environment [28] and how Parkes & Dickie created a biological imperative for interaction design [51], Living Bits is an attempt to think beyond the traditional boundaries that exist between biological cells and computers. Our paper enables someone new to the area to be able to think about a project, understand what is possible, and realize what challenges exist in doing such work. We survey and classify research projects that integrate microorganisms as part of the computing system, conceptualize their key design elements, and show how to apply the concept to future projects. Finally, we discuss the ethical and societal implications of this work. We aim to inspire the integration of biology and computing to shift the traditional perspective of HCI.

2 BACKGROUND AND MOTIVATION

In principle, biological cells "[compute] to build" [20]. A living cell could receive inputs such as chemical cues or physical signals from its surroundings to metabolize and respond to the environment. In the past decade, researchers have used the ability of microorganisms to produce outputs (chemicals, smell, taste, color, movement, and more) as part of interactive interfaces ranging from wearable devices [3, 4, 12, 40, 48, 64, 67, 67, 73] to musical instruments [35], built environments [47], food [11], games [9, 34] and robots [8, 52], demonstrating a rich spectrum of research in HCI that engages with microbes.

Though digital technology dominates modern industrialized societies, these projects demonstrate that there is a possibility to rethink computation using organic and living systems. Here, we seek to characterize and systematically study biological interfaces in the context of HCI.

2.1 The Microbe as a Bio-Computer

Compared to other living organisms, a microbe is a unicellular organism utilizing minimal biological processes and genetic materials. Thus for its simplicity, the microbe is used as one of the model organisms for studying and engineering biological computation and fabrication in modern biotechnology research. For example, bio-pharmaceutical companies have successfully inserted a human gene responsible for producing insulin in E. coli to help individuals with type 1 diabetes produce insulin [21]. Researchers have also developed synthetic biology methods to enhance the computational capabilities of microbes by designing complex genetic circuits [6, 13, 24, 69] that function as biological logic gates, as well as designing programming languages and software to create them.

These genetic circuits allow researchers to sense, compute, and actuate at the micro-scale. More specifically, the resulting genetic circuits have various applications that span from health care to environmental protection. These microbes can act as biosensors to report the presence of toxic chemicals in the environment [62] or as photoreceptors to paint images [43].

2.2 Interfacing with Microbes

Living Bits rethinks microorganisms as a programmable biological interfaces. Early works in biological HCI [53] have primarily been focused on using microbes as biological actuators [34, 50, 73] and tools for citizen science outreach [37, 39], but is still far from reaching the full possibilities as a biological computer that can enhance digital technology.

Our goals for Living Bits are to: 1) outline and inspire the possibility for HCI researchers to rethink computation beyond digital technology using organic and regenerative living systems such as microbes; 2) explore and characterize novel human-microbe interactions across contexts and scales; 3) provide principles for stimulating discussions, presentations, and brainstorms of future microbial and biological interface designs. We aim to make Living Bits accessible to researchers across HCI, synthetic biology, biotechnology, and interaction design to explore the next generation of biological HCI [53]

3 METHODOLOGY

We conducted a search across multiple existing fields (HCI, synthetic biology, biotechnology, interaction design, industrial design, speculative design, architecture, and art) using the following keywords: "Microorganism", "Microbial", "Microbes", "Bacteria", "Yeast", "Biotic", "Bio HCI", and selected example projects that are well established in each communities, have been published and exhibited to the public. The current community of practitioners and researchers working in the area of living Bits or microbial interfaces (Microbial HCI) is relatively small compared to other branches of the HCI community, so we aim to diversify the source of the projects as much as possible. We also aim to highlight different possibilities of microbial HCI by selecting projects that show creative and unique applications of microorganisms in the context of human-computer interactions. Therefore, these examples were selected to represent the rich spectrum of research within microbial HCI. The selected microbial interfaces projects included Mushtari [4], bioLogic [73], Mold Rush [34], Euglena Soccer Game [31], RGB E.Coli [15], Breathing Shoes [40], Biota Beats [35], Antibiotic-Responsive Bioart [37], OpenLH [23], My First Biolab [22], Vespers [3], Carbon Eaters [40], Social Microbial Prosthesis [12], Grown Microbial 3D Fiber Art [48], Mycelium Artifacts [71], Myco-accessories [64], Growable Robot [52], Biosensing Soft Robot [8], Empathetic living media [8], Microbial Home [47], E. chromi [11], Microbial Perfume [68], Bioelectronic soil sensing device [38], Gut-Brain Computer Interfaces [66], 3D Printed Living Responsive Materials and Devices [45]

These example projects were used as the starting point for investigation. In the process for conceptualizing Living Bits, we characterized and systematically studied the utilization of microbes as biological interfaces in each project across scales and applications. We identified and compared the unique advantages between digital and biological computers, categorized the use cases of microbes through a design rationale and proposition into different application domain of microbial interfaces. Finally, we characterized the design elements of Living Bits according to scale. We present our analysis in three parts: 1) parallels between microbial computation and digital computation, 2) different application domains, and 3) the design elements of the microbial interfaces.

Characteristic	*Digital Computer*	*Microbial Computer*
Input	Visual, Audio, Haptic	Chemical, Ion, Nucleic Acid, Antigens, Light, Heat, Magnetic Field
Process	logic computation	logic computation, gradient computation
Output	Visual, Audio, Haptic, Olfactory	Pigment, Smell, Enzyme, Motility, Cell growth, Cell death, Morphology change, Chemical
Fundamental Language	Binary code	DNA/RNA code
Scale	$10^{-2} - 10^{0}$ m	$10^{-6} - 10^{0}$ m
Speed	Fast, but discrete	Slow, but continuous
Power source	Electrical power	Microbe dependent, primarily carbohydrates (i.e. sugar) and other nutrients
Recyclability	High recycling cost, does not decompose, toxic to environment	Biodegradable or compostable

Table 1: Comparison between microbial interfaces and digital interface.

4 PARALLELS BETWEEN MICROBIAL AND DIGITAL COMPUTATION

To help someone new understand the integration of microorganisms in HCI, we provide a comparison of digital and biological computation. A living cell shares many characteristics with a digital computer in the sense that both systems can receive input information, compute, and then respond. However, both have unique advantages and disadvantages.

4.1 Information

Like other organisms, microbes contain DNA as the fundamental information system. In contrast to the binary system (0 or 1) used in digital computers, DNA is a quarterly system composed of four possible molecular digits (A, T, C, G). 215 petabytes (215 million gigabytes) could be stored in a single gram of DNA [14]. DNA sequencing could be used to "read" from "DNA memory", while gene editing technology (e.g. CRISPR) [59] could be use to "write" to DNA by changing genes, similar to changing bits in a hard drive. This has motivated researchers to explore the possibility of using DNA hosted in microbial cell as a storage system [59]. DNA stores genetic code in the form of genes responsible for different abilities

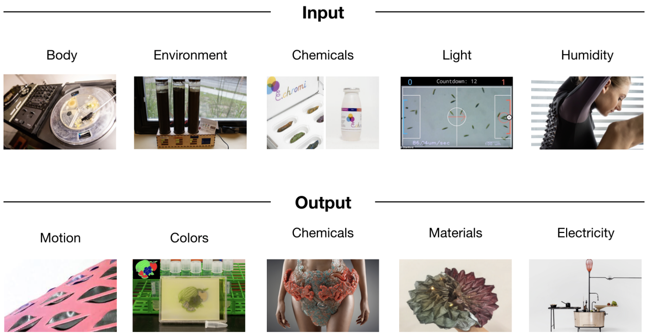

Figure 3: Example inputs and outputs that the microorganism can sense and produce.

and behaviors of the organism. The central dogma of molecular biology articulates the two-step process, transcription and translation, by which information in genes enters proteins. In this, DNA is transcribed into RNA, which is translated into proteins, an essential bio-molecule with diverse functionality. The engineering of DNA to make functional proteins is analogous to writing digital code for compiling into software.

4.2 Input and Output

In terms of input, process, and output, microbes are flexible compared to digital computers. Inputs to microbial cells can be molecular, which include chemical, ionic, nucleic, and antigen molecules [69]. Inputs can also be physical conditions of the environment, such as light, heat, and magnetic fields [15, 56, 69].

Similar to the input channel, microbes also have a wide range of output modalities. Outputs can be visual, olfactory, mechanical, and chemical [69]. Examples include producing pigments or fluorescent molecules for visual cues, releasing scents as olfactory cues, movement as a mechanical cue, and releasing enzymes that break down toxins in the environment as a chemical cue.

4.3 Computation

In digital computing, logic gates have a binary (0 or 1) output in response to one or more inputs. In synthetic biology, cells can simulate this behavior. When these biological "logic gates" are combined, it is possible to simulate digital-like computation solely using biological functions [6, 13, 70]. Researchers have demonstrated the ability to toggle biological functions in a binary fashion through genetic toggle switch in bacteria [19]. Researchers also developed complex genetic circuits [6, 13, 24, 69] with multiple logic gates, as well as designing programming languages and software to create them. For example, Autodesk developed "Genetic Constructor", a cloud-based computer aided design system (CAD) to support the design of genetic circuits using a visual language that focuses on the functional parts of the gene [5]. These genetic circuits allow researchers to sense, compute, and actuate in the microorganisms.

4.4 Energy Sources

In order for microorganisms to grow successfully, they must have a supply of water, nutrients, and gas, such as oxygen. The majority of chemical substances in microorganisms contain carbon in some form. Based on the microorganism that you are working with, there are diverse carbon sources for microbes to grow on ranging from organic materials, such as leaves and sugar, to synthetic compounds, and even waste such as plastic [58]. Certain microbes such as Cyanobacteria can fixate chemicals in the air through photosynthesis [4]. In nature, many microbes consume nutrients through biodegradation processes and play a significant role in nutrient recycling and ecology restoration. Thus, in the process of using microorganisms to perform certain functions, it can help recycle materials and create conditions for other organisms to thrive. For example, fungus release enzymes to decompose cellulose compounds in wood. In the process, "hypha" a soft branching filamentous structure of a fungus is formed. Researchers have utilized hyphae to create growable rigid structures for architecture, furniture, and other applications [71].

4.5 Size and Speed

Microbial cells are at the micron sale (10^{-6} m), but microorganism colonies can be visible to the naked eye, such as mushrooms. Microbial colonies have an exponential growth curve, but the speed depends on the species and environment. E. coli, the widely adopted model microbe, divides every 15 minutes. As the colony grows, the function of the microbe or "biological circuit" is continually executed throughout the colony.

The genetic source codes responsible for programming these diverse input, process, and output modules are open-source and available online, as mentioned in a previous section. These databases are constantly expanding with new knowledge as researchers and practitioners make new discoveries, and current knowledge can be applied to a broad array of applications. Effort to implementation is higher for individuals without a biological background; it is recommended to start with simple examples before proceeding to more advanced genetic source codes.

5 DOMAIN OF MICROBIAL INTERFACES

We identified five different categories of how microorganisms have been used as interfaces in the context of HCI: to embody, communicate, enhance, materialize, and play.

5.1 Embody

Embodied microbial interfaces are those that captures and translate digital and experimental data into something tangible. Embodiment is defined as a physical manifestation of a computational artifact or phenomenon [2]. The idea of embodied interfaces in HCI is to enrich human sensory experiences when interacting with a computer using "physically-embodied digital information in physical space" [27]. In Vesper, the researcher conceptualized the process of embedding engineered microorganism in the 3D fabricated death mask that could embody the last breath of a human being by converting chemical compounds from the breath into visible pigments: "Transitioning from vessels of representative neuro-vasculature to

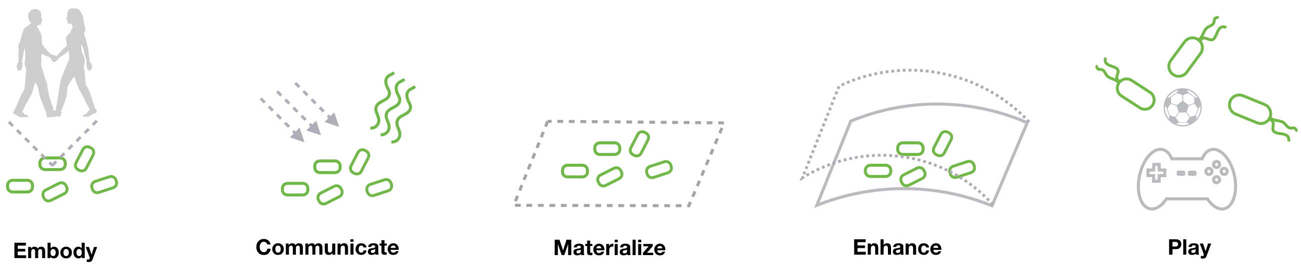

Figure 4: Domain applications of microbial interfaces.

actual biological urns" [3]. The researcher further characterized such composite materials as "Hybrid Living Materials" [60]

In Biota Beats [35], researchers explore the concept of musical embodiment by designing a microbiome record player. The player uses an algorithm to extract location, density, and cluster size from a petri dish that contain microbes cultured from different parts of the body to algorithms that generate a musical composition. The microbiome record player is currently used as an outreach tool for the public to learn about the “music of their microbiomes."

Lastly, "Living Empathetic Media" [8] demonstrates the use of microbial populations to embody human interactions. The researchers developed a closed-loop control system which measured the user's empathetic interactions to control the liquid nutrients provided to a colony of E. coli. The more empathetic interactions the user had, the more the E. coli glowed. Thus, the social interaction information is embodied in living organisms which promote empathy.

5.2 Communicate

Microbes has been used as the medium for communication through different signals across scales and environments. They work as the signals amplifier by taking the inputs, and turn it to observable and measurable outputs.

In the E.Chromi project, researchers used microbes to develop a yogurt which changes an individual's feces color in response to specific health and disease biomarkers. They accomplished this by engineering pigment production via a metabolic pathway inside the bacteria [11]. By connecting the pathway for producing visual output with the sensing modality of the cell, researchers can integrate living organisms as ubiquitous sensors that communicate surrounding information. For example, researchers demonstrated the use of stretchable, robust, and biocompatible hydrogel [45, 61] to host engineered bacteria for creating a chemical sensor that can be attached on body [44] and a robot [29].

Further, the visual signals created by the microbes have been extensively used for creative expression in the form of biological ink. Researchers had used the biological ink to engage the public in learning biotechnology [23, 37]

Beyond visual communication, microbes have also been used for scent production [68]. Further, natural signals produced by microorganisms in their natural habitats could be used as an environmental indicator. In Bio-electronic, a soil sensing device, researchers used the electric signals microbes produce in response to soil to communicate the soil quality and versatility of soil microbes. It was used as an educational tool to the public for studying ecology [38].

5.3 Materialize

Bio-fabrication is one of the largest domains of research in biotechnology and biodesign. Several types of microbes such as bacteria and fungus naturally produce bio-materials as the by product of their metabolism. Researchers have developed processes for cultivating microbes to produce biodegradable materials such as cellulose [49], mycelium [30], and others. These materials has been woven into biological interfaces across applications.

For example, artists and designers have created wearable "microbial 3D fiber art" [48] and a fashion collection: BioCouture [41] using microbial cellulose produced from Kombucha culture of yeast and bacteria.

Further, Growable robot [52] is a robot made of flexible electronics embedded in regenerative microbial cellulose. The research team proposed the application of microbial cellulose as a biological exoskeleton of the electrical system with renewable, self-healing, and shape changing properties .

In "Mycelium Artifacts", researchers used "mycelium", the self-reproducing part of a fungus containing thread-like "hyphae" to create various design forms. The project demonstrated the use of mycelium as a multipurpose sustainable bio-material for rapid prototyping, sculpting, and physical replication of 3D models [38]. Researchers also coupled mycelium composites with electronic circuits and digital fabrication techniques, replacing plastic with growable materials [63]. Moreover, the researchers proposed using biodegradable materials to create a more sustainable electronic life cycle. For example, "Myco-accessories: sustainable wearables with biodegradable materials" presents an accessory for which the electronic components can be re-used, and the wearable design composted [64].

Finally, in "Breathing Shoes", researchers collaborating with the Puma company piloted personalized biofabrication. First, they grew shoes from bacteria which respond to heat. When the heat increases, the bacteria open air passageways to lower the temperature inside the shoe. Over time, each shoe molds to the profile of their users foot [40].

5.4 Enhance

Through embedding living microorganisms inside everyday objects, researchers could tap into the biological functions found in microbes to augment the capabilities of materials and devices. This enhancement ranging from photosynthesis to shape changing ability could lead to a symbiotic relationship between human and the microbes. *Nature: Collaborations in Design* features diverse examples of projects that aspire to establish this symbiotic relationship [10].

For example, Mushtari is a wearable embedded with synthetic microorganisms that can augment human biological functionality for space travel. Researchers 3D printed wearable fluidic channels containing two genetically engineered microorganisms: a photosynthetic microbe such as microalgae or cyanobacteria that converts sunlight to sugar, and compatible microbes such as yeast and E. coli that convert sugar into useful materials for the wearer such as drugs, food, fuel and more [4]. Alongside the design for the extreme environment, "Carbon Eaters" is a small round button containing algae "Oscillaloria" that absorb and respond to carbon dioxide in the air, changing colour to indicate air quality and the presence of high levels of substances to improve the performance of the wearer [40].

Further, bioLogic is a responsive bio-skin using living actuators created by an automatic deposition method for printing bacteria cells on soft materials [50]. With environmental humidity changes, the cell grows and shrinks, which influences the material to change its shape. The researchers have demonstrated various use cases of the technology from applying the microbial actuator on fabric to creating a synthetic bio-skin that reacts to body heat and sweat. The design of the bio-skin includes flap structures around heat zones that open and close for cooling down the body [73]. Researchers also show the ability to actuate robots using molecular motors assembled into multiscale ensembles [55].

Beyond wearable devices, Microbial Home [47] is a collection of appliances that integrate microorganisms into the design for making homes more self-sufficient and less wasteful of natural resources. The project includes six integrated pieces that heat, refrigerate, digest and generate food using microbes to recycle nutrients. The central piece of the project is the "Methane Bio-digester", a kitchen table that collects food waste for bacteria to produce biogas. The gas powers the lights and water heating components in other parts of the system. Other key designs in the collection include "Paternoster" - a device for up-cycling plastic into mushrooms, and Bio-Light, an array of glass cells containing bioluminescent bacteria that can be hung on the wall as a biological light bulb [47].

5.5 Play

Researchers have introduced the concept of a "biotic game", a game that incorporates a biological system as the gaming element. The biotic game is created to motivate student learning at the intersection of life sciences and device engineering [9]. The game uses the real-time interactivity of living microorganisms "turning classic observational microscopy into an interactive experience" [32].

In Euglena Soccer Game, the player needs to score points by observing and controlling the position of a Euglena cell to shoot a virtual ball into the goal. Euglena is a microorganism with a whip-like appendage called flagella used for moving around. The game developers used "phototaxis", a behavior of Euglena where the cell moves toward light. Thus, the player orients the Euglena using 4 LEDs, one in each corner. By tapping the "Shoot Ball" button, the ball is shot in the direction of the current Euglena orientation. The Euglena Soccer Game was one of the pioneering biotic games that inspired many game researchers and developers to integrate living systems in game design [31].

One of the games that was inspired by the Euglena Soccer Game is called Mould Rush. Mould Rush is a hybrid physical-digital multiplayer strategy game, that is played on a slow but constantly-evolving biological landscape of living microorganisms such as bacteria, yeast, and fungi. As different species of microbes (with different colours and shapes) grow and move across a nutrient terrain, they are digitally captured with a high-resolution scanner for the players to observe any physical changes when they occur. The goal of Mould Rush is to compete with fellow players and collect as many microbial cells as possible, over a five-day period. Points are awarded based on the coverage of cells on the selected segment, and it is calculated using an image processing tool. The research team discovered that the "slowness of microbial growth may not necessarily compromise playing experience, but rather, enhance it instead" [34] showing a promise for the future of interactive biotechnology.

6 DESIGN ELEMENTS

The projects presented in the previous section demonstrate how HCI researchers have already begun paving the way to biological interfaces by exploring how to work and design with microbes [53]. This body of research is growing, and there are many more possible future directions. However, to systematically understand biological systems for an HCI perspective, we will describe Living Bits in 5 levels: cell, colony, system, interface, and interaction. We arrange these levels from smallest to largest scale.

6.0.1 Cell. The fundamental unit of Living Bits is the cell. When setting forth to create an interaction, the designer could adopt the natural abilities of a microbial cell for an interactive system. For example, Acetobacter bacteria can develop microbial cellulose to serve as the self-building body of a robot used in Growable Robot. The microbial home uses the natural ability of microbes to digest food waste and produce bio-gas.

If the natural abilities of a microbe are not suitable for the interactive system, synthetic biology techniques can be used to modify these properties. For example, in E. Chromi, bacteria are engineered to turn a specific color upon encountering biomarkers for disease in the GI tract. When excreted, the color of excrement will signify whether the disease is present in the body. The well-characterized microbial model systems, such as E. coli, yeast, and algae offer a solid foundation for synthetic biology exploration [36].

In the past decade, accessible methods and protocols for engineering biology have been published for the DIY community such as BioBuilder (Book) [36]. The synthetic biology process follows an engineering cycle through design, building, and testing phases. The first step is to design the biological circuit to insert into the microbes through browsing DNA libraries to find specific genetic

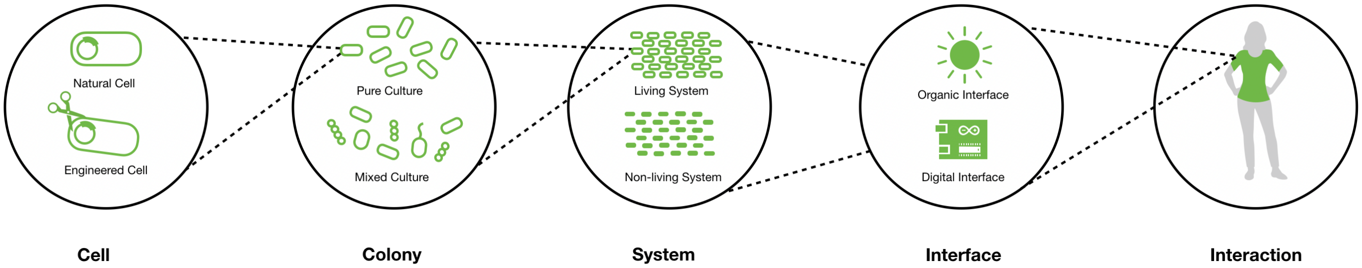

Figure 5: The five levels of microbial interface elements.

parts that serve the intended applications. The second step would be to synthesize and fabricate the gene construct using a DNA synthesizer and other biological assembly methods, and finally to inject the genetic construct into the host microorganism, a process referred to as 'transformation,' to test if the circuit could execute its designed function inside the living system.

6.0.2 Colony. A colony is a group of microbes living in the same environment. Colonies can be pure, consisting of a single type of cell, or mixed. Interactive systems can adopt pure cultures for a specific purpose. Biologic used a pure culture of Bacillus Subtilis natto, the cells of which expand and contract in reaction to atmospheric moisture, to open the shirt flaps and allow sweat to evaporate. Interactive systems can also be driven by mixed culture properties. For example, Biota Beats uses properties of different colonies from the body (hands, feet, etc.) to generate music. A designer could also create a symbiotic environment that advantageously combines mixed microbe types that augment each other's abilities [25]. In Mustashi, the design combined Cyanobacteria and other complimentary microbes into a colony that can harvest sunlight to create sugar, and use the sugar to create other useful materials. Growable Robot also combined yeast and bacteria to co-produce cellulose for the robotic body.

6.0.3 System. The system is a combination of both a pure or mixed colony and its byproduct. The designer could create a living system or use the non-living materials produced by microbes. A consideration for the living system is that it requires resources such as nutrients and oxygen to stay alive. For example, Microbial House is a kitchen table that integrates microbial incubators, so living microbes can recycle food waste into bio-gas. Non-living products from the microbes could be a pigment used in E. Chromi, mycelium used in Myco-accessories, or microbial cellulose used in the Growable Robot. These products are used in the interactive system regardless of the living microbe.

6.0.4 Interface. The interface is the way that the microbial system interacts and communicates with the surrounding environment. A designer could use digital [33] or organic interfaces to read inputs or provide outputs. Digital interfaces can use sensors and actuators to convert biological activities to digital signals and vice versa. For example, a gut-brain computer interface (GBCI) uses electrodes to collect electrical activity of gut neurons [67], which are influenced by the microbiome. The Euglena Game uses lights to guide the movement of photo-sensitive microbes. Biota Beats and Biosensing soft robot use cameras and computer vision algorithms to track visual markers of microbial growth. On the other hand, an organic interface can use nutrients, humidity, molecular cues, and pigments as inputs and outputs as demonstrated by bioLogic, Wanderer, and E. chromi.

6.0.5 Interaction. The interaction level concerns the way in which the individual interacts with the microbial interface. The interaction can be a one-way interaction or a complex feedback loop.

In a one-way interaction, the human provides an input that creates a desired result. For example, a person provides samples for bacterial cultures from different parts of the body in Biota Beats to make music. Or, such as in the RGB bacteria project, a person uses optogenetic tools to direct red, green and blue (RGB) light on E. coli bacteria whose gene expression changes upon RGB light. The end result is a "photograph" made on a bacterial culture.

In a two-way interaction, the human changes their actions based on feedback from the microbe. In a GBCI, a person would change their dietary, sleep or stress habits to improve their microbial health based on feedback from the device. In the Wanderer, a person would change the input from their body to produce usable energy from bacteria.

7 APPLYING LIVING BITS TO A PROJECT

The use of microbes as computers is not limited to scientists and researchers in academia or industry. DIY (Do-it-yourself) and citizen biotech communities have been making progress toward democratizing biotechnology and synthetic biology genetic source code, knowledge and protocols. This community includes artists, designers, tinkerers, scientists, and hackers. The practices, tools, and challenges of the biotech community have also been studied in the context of HCI [16, 39].

One of the most influential platforms for synthetic biology education is iGEM (International Genetically Engineered Machine Competition), where participants from around the world ideate, design, build, and test genetically engineered organisms for a wide variety of applications. The development of well-specified, standardized, and interchangeable biological parts is a critical step towards the design and construction of integrated biological systems. The Registry of Standard Biological Parts hosted on the iGEM platform supports this goal by recording and indexing biological parts and offering resources to construct new parts, devices, and systems [1].

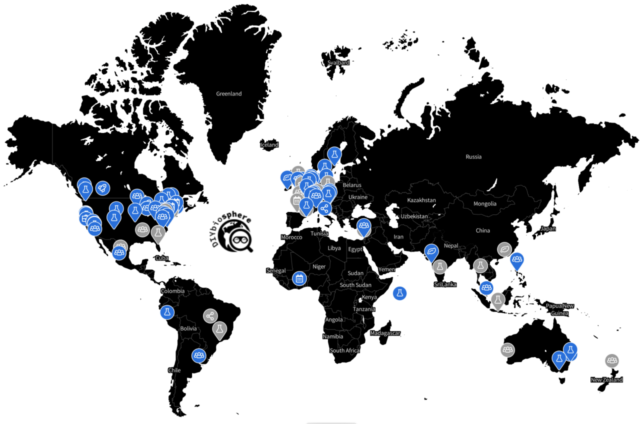

Figure 6: A screen capture of DIYbio Sphere, an online interactive map of labs, incubators, networks, events related to citizen biotechnology.

As the citizen science community continues to grow, microbes have become the key material entry point to the world of biotechnology. Many open source protocols on how to isolate, cultivate, and engineer microbes using everyday materials and tools are becoming available to the public.

Moving forward, applying the concept of Living Bits to design research could be an intimidating process as every paradigm shift requires courage, a spirit of experimentation and exploration. Whether you are a HCI researcher in industry, academia, or any other background, it is possible that you could use microbes to augment your design in multiple ways. From the author's experiences working, researching, and talking to other researchers who have worked in the area, we came up with four steps that may help integrate microbes into HCI projects.

7.1 Deciding what microbes are right for your design

This paper has categorized and showed several examples of how living microorganisms could be used in interactive systems across scales, contexts, and applications. Understanding the challenge that you are trying to solve is the key for getting started. Looking at the advantages, disadvantages, and characteristics of biological and digital systems discussed in the prior sections is fundamental to answering whether the biological system is appropriate for your challenge. For example, if you are a HCI researcher working with wearable technology developing a new body sensor, you would discover in this paper that there are artists and designers who design with microbes, using them as creator of regenerative flexible second skin interface [4, 41, 48]. Thus, this might inspire you to embark on a journey to integrate them with the sensor you are working on.

7.2 Designing your system

Once you decide to design with microbes, referring to Figure 1, which lays out the microbial cell architecture. The figure could provide a mental framework for the integration of microbes in your design. By analyzing the input, process, and output of your microbes, you could use them to specify different elements in the microbial interface design. In the hypothetical scenario where you want to find a way to integrate a "microbial second skin" with your sensor, you would follow the microbial cellulose articles cited in this paper to understand more about the process for cultivating the microbial cellulose. Afterwards, you could realize a microbial cellulose by cultivating bacteria and yeast found in kombucha drinks, giving the microbes carbohydrates (sugar) as the input. The microbe would process the carbohydrates monomer into a cellulose polymer sheet. You would also think about how would you place your sensor in the microbial container, so when the microorganisms grow, they can seamlessly fuse with your sensor.

7.3 Finding resources

After you have developed an understanding of how the microorganisms could be integrated into your design system at different levels according to the framework, you could perform additional research to find specific protocols and instructions on how to cultivate or engineer the microbes to have specific desirable functions. Many biological standardized parts, protocols, and past projects are available online on the iGEM website as an inspiration and repeatable instructions. Many open source tools for cultivating microorganism such as DIY incubators [16] are also available on many citizen science websites. If the system that you are trying to build require sophisticated engineering tools and protocols, it is advisable for the user to find relevant research in academic journals or conferences that publish in-depth studies on microbiology or synthetic biology. Reaching out to experts for collaboration is also highly advisable. In many cities, there are citizen science, or "community biology" laboratories, which could provide access to local expert as well as a laboratory space. Newcomers can locate the community labs, incubators, networks, events related to citizen biotechnology by browsing DIYbio Sphere, an online interactive map of organizations involving biotechnology.

In our scenario, since the microbial cellulose project does not require either the pure microbial culture, or the pathogenic microbe, you would learn from the paper that you could do it by yourself. You could decide whether you want to collaborate with other researcher, or grow the kombucha microbes by yourself. If you decide to grow them by yourself, you would prepare your sensor and find the materials such as kombucha drink, sugar, tea, liquid container described in the paper, and locate the area in your work space to start incubating them according to the protocol. Once the process is done, you will have your first microbial interface project.

7.4 Growing the project and growing the community

Biotechnology has become democratized and increasingly more open-source thanks to the efforts of a global community of researchers from multiple disciplines. These efforts have made the diverse and exciting projects related to microbes possible. We recommend that as you continue to grow your project, you could also share some experiences and lesson learned with the larger biotech community by joining and participating in local or global biotech events. Examples of events include iGEM, the Global Community Bio Summit, and SynBioBeta. Establishing ethical community norms is also important as biotechnologies proliferate. For example, at the Bio Summit 3.0 conference, hundreds of participants co-created a "community ethics" document, articulating 12 ethical principles for laboratories to adopt when working with the life sciences and biotechnology. We believe the intentional co-creation and adoption of such ethical principles is critical to the safe and secure exploration of biotechnology and Living Bits.

8 THE POTENTIAL IMPACTS AND CHALLENGES OF LIVING BITS

Living Bits offers the opportunity to harness natural properties of microorganisms either in or beyond traditional computing paradigms and architectures. It can have positive impacts on our digital life, health, and natural environment. However, technical, societal and ethical challenges remain. Though the categories are not exhaustive, we aim to stimulate discussions and debates about the future of microbial interfaces, even biological HCI at large, and its impact on society.

8.1 Environmental Impacts

"Digital life" herein is defined as the relationship and ecosystem society has built around devices with computers or micro-controllers with digitally represented data. Our digital life creates waste for the environment and harmful stimulus for our health. Microbial design can offer less disruptive interactions between individuals and media. TVs, smartphones, computers and subsequently their applications produce visual stimuli that disrupt our sleep cycles [42]. Instead of LCD screens, displays could one day adopt bioluminescent bacteria [15]. By using visual stimuli in ranges of the electromagnetic spectrum that do not cue our circadian rhythms, may lead to fewer sleep disruptions.

One of the emerging themes from the example projects is the use of microbes to create sustainable and renewable materials. The electronic life cycle produces environmental polluters and exposes humans to toxic materials at multiple stages of production. Microbes synthesized in laboratories can offer alternative materials for lead, mercury, and even rare-earth metals. Some of these metals continue to be harvested in territories that potentially use child labor [46]. Instead of relying on inorganic material, devices can be created from microbial organisms and their byproducts sustainably grown in laboratories. For example, "traces" in circuit boards can be created using ion channels bacteria currently use to communicate by electrical activity [54].

Furthermore, when electronics become obsolete, they become "E-Waste." E-waste cannot decompose. It releases endocrine-disrupting chemicals (EDCs) into the environment and food chain that are later metabolized by gut microbiota with toxic effects; this effect has even been linked to the global diabetes epidemic [65]. E-waste contains other materials toxic to humans. The negative impacts disproportionately affect individuals in low-income communities or in developing countries [7]. Instead of being made with EDCs and other materials harmful to humans, electronics could be created in part or one day in full using organic material. For example, plastics can be replaced by cellulose [52]. Though the production of organic materials still produce waste, they can improve the environmental and social impacts of electronic production and disposal.

8.2 Technical, Societal and Ethical Challenges

Though standardized biological parts and protocols are becoming more open-source, there is a gap between the community of HCI researchers, interactive designers, and biologists. We believe this gap is caused by, 1) the lack of a holistic accessible to people across backgrounds, 2) the actual or perceived lack of access to wet-lab space and materials, and 3) the nature of biological systems that make them more unpredictable than digital systems. In this paper we aimed to address 1) and 2) by explaining key components of microbial systems in accessible terms and references to open-source resources. However, because we do not have a complete understanding of biology, we must assume that unpredictable behavior may occur more frequently than with digital devices. We hope to encourage HCI researchers to "approach non-living and living matter as a continuum for computational interaction" [51].

Living Bits raises ethical concerns regarding the integration of biological matters as design elements. We know synthetic biology has potential to affect all persons, positively and negatively, yet we do not have a complete understanding of biology. It may be difficult to predict and control outcomes of experiments and projects.

Further, manipulating the genetic materials and behaviors of microbes in the design process may contribute to anthropocentrism, a problematic point of view that humans are the only important entity in the ecosystem. In this paper, we study microbial interfaces in the context of *human*-computer interaction, which may support this notion. Living Bits is the idea of co-existence computation, therefore the researchers that work with microbial interfaces should think of human-microbe interactions as a symbiotic relationship rather than the materialistic exploitation of biological entities.

In response to the rapidly evolving body of biotechnology research, *New directions: The ethics of synthetic biology and emerging technologies* compiled views on the science, ethics, and social issues of synthetic biology. The book was published by the U.S. Presidential Commission for the Study of Bio-Ethical Issues (PCSBI) which gathered and analyzed input from public meetings, open forums, and interviews with scientists, engineers, faith-based and secular ethicists, and the general public. Though it focuses on basic scientific research, it can be extended to microbial HCI research. *New Directions* identified five ethical principles: (1) public beneficence, (2) responsible stewardship, (3) intellectual freedom and responsibility, (4) democratic deliberation, and (5) justice and fairness [18]. Here, we define and contextualize these principles for microbial HCI, with an important limitation.

Given that *New Directions* and the authors sourced opinions that were WEIRD (Western, Educated, Industrialized, Rich, Democratic) [26], we must assume a limitation that it may not extend to all cultures worldwide.

8.2.1 *Public Beneficence.*

Public beneficence is maximizing public benefits while minimizing public harm, and promoting activities with the potential to improve well-being. From the landmark Belmont Report on ethical principles for research involving human subjects, beneficence requires not only treating persons in an ethical manner, but putting in effort to secure their well-being [17].

For synthetic biology this extends beyond the individual to the institution, community, and public at large. When considering the integration of microorganisms in HCI projects, it is important to ask: What are the benefits and risks of this project? Does it have the potential to contribute to public good? What are the strategies, specifically, that researchers will take to minimize harm and maximize benefit?

8.2.2 Responsible Stewardship (123). Responsible stewardship is to establish processes for assessing benefits, risks, safety, and security before and after projects. It is crucial researchers have the safety training required and appropriate for the microbial HCI project, e.g. wet lab training. In addition, researchers can establish partnerships with field experts (as discussed in 7.3 Finding Resources) to transfer knowledge, resources, and processes for microbial HCI projects.

8.2.3 Intellectual freedom and responsibility (141). Intellectual freedom and responsibility advocates for the balance between creativity and oversight. During the process of designing a microbial HCI project, it is important to consider which institution or individual is ensuring oversight, security and safety. Before implementing a project, it is recommended to consult this resource to evaluate responsible stewardship and public beneficence.

8.2.4 Democratic Deliberation (151). Democratic deliberation includes respectful debate of opposing views, the ongoing exchange of ideas publicly, and “careful attention to processes through which decisions are reached and justified.” Researchers should open the opportunity for public input through multiple methods. For in-person feedback, this could include organizing meetings to discuss the ethical implications of future microbial HCI research projects and inviting members of the community, via email lists, flyers, and post. If conducting user studies, researchers can include free-text survey questions or semi-structured interview questions asking participants to provide their opinion on e.g. the benefits and risks (beneficence) of the project. Online, this can include blog posts accompanied by open calls on social media platforms to gather feedback and input. In online forums, we recognize the possibility of trolling. While identifying these comments, researchers should continue to welcome critical thoughts on work and general feedback.

Next, researchers should analyze the decision-making process behind the project. Which individuals, groups, and institutions were involved? What are their interests and concerns, and what kind of resources did they invest in the project (time, funding, equipment, etc.)? The answers to these questions should be public, accessible, and unobscured, and made available to all affected parties in their primary language (see Justice and Fairness).

8.2.5 Justice and Fairness (161). Justice and fairness calls for prevention of unjust distributions of benefits, burdens, and risks. In the context of microbial HCI, this means returning to beneficence and analyze the distribution of benefits, burdens, and risks among individuals, groups, and communities. Researchers should ask questions such as: whom was this technology designed to benefit? Based on implementation and dissemination, who actually benefits from the technology? What are the negative side effects of the project, and which individuals and communities bear the burden of this? How many communities does the project reach (tangibly or through media and communications)?

9 CONCLUSION

Microorganisms formed the foundation for human life. Their existence predates ours by 3 billion years [57], and is crucial to the basic functioning of our brains and bodies. In addition, we have adopted microbes as a technology: we have worked with microbes to ferment food and alcohol for thousands of years all the way to genetically modifying microbes to cure disease today. It is understood that digital life exists orthogonal to microbial life. However, it does not have to stay this way.

Recent advances in synthetic biology have led to the ability to adopt microbes as computers. These tiny organisms can be "programmed" to accept a wide variety of inputs and subsequently exist in binary states, akin to logic gates that form the basis of computing. But these organisms have an incredibly wide array of capabilities compared to a traditional circuit. They can self-heal by growing and multiplying without outside interference; they can create renewable materials and energy; and even turn specific colors to report human health and disease conditions. All of this in a package a thousandth of a meter or smaller.

Living Bits aims to bridge the digital and the microbial. We show how researchers have integrated microorganisms into technology projects. Further, we explain parallels between computing components and microbial components to help someone new understand and approach this emerging area. We explain each level of scale for the Living Bits, from the cell to the colony, and classify microbial projects. Lastly, we provide resources and an ethical perspective to further help guide the reader in the direction of microbial interfaces. Through these contributions, we aim to help researchers understand microbial HCI and its opportunities and challenges.

Living Bits allows someone new to the area to be able to think about a project, understand what is possible, and realize what challenges exist in doing such work. We believe that as we integrate biology and computing, we can shape a new era of HCI beyond the digital, towards organic computation through regenerative living systems.

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