Designing Direct Interactions with Bioluminescent Algae

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Figure 1: Physical kinetic interactions with Dinoflagellates (bioluminescent algae) in a (a) closed environment, (b) porous environment, and (c) open environment.

ABSTRACT

Living matter is an emerging topic of interest in HCI as researchers are recognizing the unique affordances of biological materials. We explore direct interactions with Dinoflagellates, bioluminescent algae that produce light when exposed to oxygen through physical stimulation. Leveraging Dinoflagellates' natural feedback mechanism, we propose directly engaging the human user with the organism through physical kinetic interactions. We take an organism-centered design approach, considering the well-being of the organism by focusing first on designing appropriate environments for the organism, then proceeding to exploring the available interactions within these environments. Our framework consists of four components (form, reception, feedback, and control) and can be used to guide designers in their design process with living matter. We demonstrate the framework with environments for Dinoflagellates and three real-life examples: a checkers game, a ball game, and hopscotch. Last, we discuss the constraints and limitations of integrating Dinoflagellates and living matter in interactive systems.

CCS CONCEPTS

• Human-centered computing → Interaction design.

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KEYWORDS

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1 INTRODUCTION

HCI researchers and interaction designers have recognized the unique abilities and affordances of biological materials and are leveraging them in the design of interactive interfaces and systems [8, 24, 51, 57, 59, 60], not just by imitating nature (i.e., biomimicry [49]), but by using the natural habitats, behaviors, and metabolisms to think of new interactions and experiences [57].

Microorganisms, have been thought of as "living computers" on, inside, and around the human body, with the ability to receive inputs, process information, and respond to their environment [23]. Algae, bacteria, and fungi are only some examples of organisms with sensing, and computational abilities that may be integrated with interactive systems, potentially disrupting the traditional model of human-computer interaction systems "without the explicit requirement of a traditional computer" [51]. Essentially, incorporating biological materials in interactions positions living matter as the medium through which we manipulate and experience our world.

Living Media Interfaces (LMIs) [51], for example, are interfaces which incorporate living organisms and biological materials in artifacts to support interaction between humans and digital systems. Living Bits [60] proposes thinking of microorganisms as

programmable biological interfaces, beyond the "traditional boundaries" between living matter and digital computers.

However, the human-living matter relationship in these interfaces is mostly mediated and indirect. To truly explore the intimate qualities of interactions with living matter, we ask if it is possible to design experiences that facilitate *direct* and *physical* interactions with living matter? This is technically challenging since living matter needs to stay sterile in order to survive, doesn't always accept human touch and body temperature, and in many cases responds and reacts over time, making the interaction delayed and "reducing" the actual interaction effect. In order to move closer to physical and direct interactions with living matter, we chose to explore the interaction nature with Dinoflagellates; bioluminescent algae.

Bioluminescence, the result of a chemical reaction that produces light in a living organism [11] is observed in a variety of marine organisms [73], one of them being Dinoflagellates (see Figure 1). When physically stimulated, the oxygen in their environment increases, causing a luciferin-luciferase chemical reaction and production of light. In their natural habitat, light from the chemical reaction appears in ocean waves which carry the Dinoflagellates. Essentially, movement stimulates an interaction with oxygen, creating the chemical reaction, and light phenomena. This mechanism can inspire HCI researchers and Interaction designers to think of incorporating Dinoflagellates in physical interactive systems, replace light-emitting components (e.g., LEDs), and utilizing them in movement-based interactions [30].

However, in this work we aim to shift away from previous approaches of using living matter in interaction design as strictly *materials*, *tools*, or *controlled media*, and towards a *relationship* between the living organism and the human user. We do so by proposing an *organism-centered* design approach, inspired by more-than-human notions of design [13, 54, 71] and the livingness of the organism [35] at the center of the interaction. In order to preserve the livingness quality of the organism and prioritize its needs and well-being, our design approach focuses first on the *environments* in which the organism can thrive in and proceed to explore the available interactions within those environments.

We present a design space exploration with Dinoflagellates, presenting three environments (closed, porous, and open) that facilitate direct and physical interactions with Dinoflagellates. We analyze each environment following an organism-centered framework that consists of four components (form, reception, feedback, and control) and can be used to guide designers in their design process with living matter. Within each environment, we demonstrate potential physical kinetic interactions, and then showcase three real-life examples: a checkers game, a ball game and hopscotch. Lastly, we discuss the unique potential in designing with Dinoflagellates, while reflecting on challenges and opportunities, possible avenues of interaction, and possible ethical implications.

2 RELATED WORK

2.1 Dynamic and physical interaction

Interaction models by Norman [55], Verplank [74], and Cooper [12] emphasize the importance of users' experience during interaction, thus closely coupling the user with the dynamic system. A more

recent direction emphasizes kinetic design in interaction, i.e., embedding organic physical motion [2, 58, 64]. The physicality within the interaction inherently holds the advantage of immediate feedback from the physical objects as the human grasps and manipulates them [31, 32]. In this work, we extend this domain by exploring interactions between humans and living matter, that are dynamic and physical, thus not facilitated by other means (i.e., digital or computing). Specifically, we design *physical kinetic* interactions with Dinoflagellates: bioluminescent algae that react to movement by producing light.

As mentioned, interaction with a dynamic system is characterized by a *feedback loop* [7], an archetypal structure leveraged by canonical models of human-computer interaction [16]. In a feedback loop (or a self-corrected system), the information flows in the environment between the system and the user multiple times until the desired goal is achieved. In this work, we reflect on the feedback loop model by exploring and designing *physical kinetic* interactions with Dinoflagellates - bioluminescent algae. The human directly stimulates the Dinoflagellates through physical movement, and immediately witnesses the light produced. The sensory experience extends beyond solely the visual feedback (light is produced in response to physical movement) as the interaction is kinetic - involving the movement of the human body. Thus sensing the interaction is experienced holistically with the human user's body. We argue that this type of interaction is fundamentally different from interactions with a visual display, as it holds physical affordances for both the human and the living organisms.

2.2 Interaction with living matter

Designing with living matter has become increasingly common in HCI and interaction design [35, 51, 60], as living organisms have unique abilities and affordances that can be leveraged as inputs and outputs of interactive interfaces. In this work, we are in particular interested in the living matter's ability to engage human users through being alive, and in their potential to capture, embody and communicate experience. Recent advancements in biology and material sciences have made new forms of interactions with organisms possible, while the rise of the DIYBio movement has played a major role in making biological tools and procedures accessible to designers and HCI researchers [20, 22, 42].

Common topics are in animal-computer interaction [47], human plant interaction [41], and living media interfaces [51, 68]. Rafigh [26] uses mushrooms to encourage children to achieve more learning goals in a tablet application, while Infotropism [28] uses corn plants to reinforce recycling as a behavior. bioLogic [81] embeds flaps containing natto cells that act as biosensors in a dancer's costume: the natto cells can detect moisture from the dancers' body (sweat) and actuate the flaps to allow air circulation. Semina Aeternitatis [1] engineers K. rhaeticus to create a tangible interface, telling a story that can be touched, smelled, and tasted.

So far, most of the research efforts have been focused on developing interactive systems that have precise control over the organisms, programming them to perform in a specific way that (almost exclusively) serves only the human user. For example, Trap it! [45] is a human-biology interaction (HBI) game that allows players to interact with Euglena by drawing on a touchscreen, triggering a

photophobic response from *Euglena* and trapping the organism before they manage to change their swimming motion and escape. The game exploits *Euglena*'s survival reaction to strong stimuli (the light intensity used to trap the *Euglena* is outside its habitual range) in order to achieve precise control over the organism's behavior. Similar mechanisms have been used to implement a soccer game and a PAC-MAN game with *Euglena* and *Volvox* [39]. We strongly believe that the interaction with living matter can reach beyond the notion of the organism being a material. Thus we propose an organism-centric approach that establishes interaction boundaries based on the comfortable environment of the non-human organism. Our aim is to shift the perspective from living matter as strictly a *material or controlled medium*, towards a *relationship* between the living organism and the human user as two counterparts.

Karen El Asmar's speculative design work touches on the relationship between the human and other organisms, by reframing humans as super-organisms, living in symbiosis with their own microbiome. El Asmar envisions a social microbial prosthesis (wearable), capable of analyzing the human user's microbiome and displaying the information directly on the skin of the user, rather than storing it in databases owned by companies [17]. In this work, we advocate a design practice that recognizes and emphasizes that the non-human organism is *alive*, resonating with Karana et al.'s work [35] on the *livingness* of organisms as a design quality. We present our exploration in designing various types of interactions with Dinoflagellates (bioluminescent algae) and propose a design framework that designers can use to consider the *livingness* of the organisms and thus prioritize their needs.

2.3 Light as an interaction modality

Light has been explored as an interactive component in numerous contexts and forms ranging from LED-based interactions in displays or objects [27, 29, 52, 82, 83], that respond fast and in real-time, to using light as a trigger agent in slow displays based on photochromic [33] or photocatalytic textiles [4]. Electroluminescent materials [3], such as phosphor powder, have been used to transform paper into an active display [21] and to create stretchable films that can be embedded in furniture (e.g., a strip lamp [38]), accessories (e.g., an umbrella that lights up when rain drops touch it [36]) and wearables (e.g., sports leggings that glow more in reaction to the amount of physical activity by the human [37]). DeLight reports a significant impact of immersive light experiences on the stress levels of the users [82].

Researchers explored the use of light in a *living* context, either using light emitted directly by a living organism [11] or using light to control a living organism [34, 39, 45]. Empathetic Living Media [11] uses transgenic bacteria (fluorescent *Escherichia coli*) to display the social media interactions between colleagues in the workplace. The system controls the amount of food the bacteria receives, thus making its glow stronger or weaker, according to the data. Genesis [34] enables the users to control remotely, via internet, an ultraviolet light that shines on colonies of transgenic bacteria (fluorescent *Escherichia coli*), some of which were modified to contain an encrypted passage from the book of Genesis in the Bible. The ultraviolet light can potentially cause mutations, or even gene

transfer between the different types of bacterial cells, essentially changing the passage and welcoming new meanings.

In this work we address a specific type of living light, bioluminescence - a phenomenon that occurs within organisms through the oxidation of the luciferin molecule by the luciferase enzyme [80].

2.4 Interaction with bioluminescence

Bioluminescent organisms contain within themselves the light source, as opposed to fluorescent organisms that depend on an external light source to charge before they glow. Bioluminescence can be found in fungi [15], algae [10, 65, 66], bacteria [18], and insects [77]. In this paper, we work with Dinoflagellates - single-cell bioluminescent algae, common mostly in marine and some fresh water habitats [10, 65, 66].

Most of the works so far have focused on using the bioluminescent organism as a material or capturing the bioluminescence and displaying its glow directly or digitally. Similar to fluorescent bacteria, bioluminescent bacteria have been used as a prime material for painting on an agar substrate. Biolumination (Queensland Museum, 2016 [78, 79]) is an art exhibition collecting living paintings with bioluminescent bacteria made using the photogram technique. To do so, the image is printed on a transparent foil, placed on top of the freshly inoculated dish and exposed to UV light; the UV light kills only the bacteria it can reach through the transparency, and the result is a high-precision image made of bacterial growth. Using a camera placed on top of a petri dish, Living Light captures the growth of *Aliivibrio fischeri* (bioluminescent bacteria) over four days [40]. The time-lapse of the bacterial growth displays two different directions: an increase in bacterial size (the lines become thicker) and a proportional decrease in their light intensity, as the bacteria slowly ceases to glow once it reaches the threshold density. Mark Rober's work displayed bioluminescence in a fountain installation that contained *Pyrocystis fusiformis* (bioluminescent algae) [67] and Erika Blumenfeld's videos of the glowing algae aim to increase awareness of our civilization's impact of the marine ecosystem [5].

To the extent of our knowledge, Andreas Greiner's Toccata for *Pyrocystis Fusiformis* [25] and the Infinity Cube by artist Iyvone Khoo and scientist Michael I. Latz [43] are the only works that address *interaction* with bioluminescence, rather than its glow and materiality. In Greiner's art installation, containers of bioluminescent algae are placed on top of a piano's keyboard. When the piano is played by the exhibition visitors, the vibrations propagate to the containers and trigger the algae to glow [25]. Infinity Cube is a multimedia installation that utilizes projections, reflections, and sound to create "a sensorial space of visual and sound stimuli" [43]. In this work we take interaction with bioluminescence further by exploring its *direct* and *physical* aspects.

3 BIOLUMINESCENCE MECHANISM IN DINOFLAGELLATES

Dinoflagellates can be observed in marine environments such as the Baltic Sea, Scandinavian Fjords, Puerto Rico bays, and the Gulf of Thailand [53]. When agitated by movement, such as shaking, brushing, and pouring (see Figure 1), Dinoflagellates are exposed to oxygen and illuminate as a result of a luciferin-based chemical

reaction [10] - luciferin being a molecule that produces light energy when oxidized. The result is a blue-green glow (see Figure 2) that can be best observed in the dark (see Figure 1). The common understanding is that Dinoflagellates use bioluminescence to startle and detract predators, and it can be assumed that this defense mechanism is not self-harming [10, 65, 66]. Dinoflagellates have limited endurance, meaning constant stimulation will tire them, and they will lose their ability to glow until they recharge. As shown in Figure 3, to induce photosynthesis, Dinoflagellates need light for 12 hours a day, as well as carbon dioxide (CO₂). Both CO₂ and light are energy sources for the algae, while the presence of oxygen triggers their bioluminescence.

Figure 2: Microscopic view of *Pyrocystis fusiformis* - the specific strain of Dinoflagellates we used in this work. (a) The *P. fusiformis* cell in the ambient light, and (b) showing blue-green glow when the surrounding light is dimmed.

For this work, we purchased a starter culture of a specific strain of Dinoflagellates called *Pyrocystis fusiformis* (see Figure 2) from PyroFarms (PyroDinos) [62]. As shown in Figure 2, *Pyrocystis fusiformis* is an oval-shaped, elongated cell, of a relatively large size for micro-organisms of the same type. A single cell can measure up to 1 mm, making it visible to the naked eye. *Pyrocystis fusiformis*'s behaviour has been intensely studied in the laboratory [10, 65, 66] as part of an effort to decipher the light-shade adaptation mechanisms that bioluminescent algae use.

To provide the right food source, we needed the specific ingredients that recreate a marine environment, that is a water solution with salinity of 3.5% and specific gravity ranging between 1.012 and 1.024. Such ingredients can be found in aquarium stores; we used Instant Ocean from PetSmart [61]. We further added to our marine solution the specific nutrients that are preferred by Dinoflagellates, commonly known in microbiology as F/2 media [56]. We purchased the two parts of the F/2 media from Fritz Aquatics Pro [63]. Table 1 shows the costs of the biomaterials (including the living organisms) that we need to start growing the Dinoflagellates.

Last, we built a photobioreactor, an apparatus that facilitates the growth of Dinoflagellates by providing the right conditions. We used commercially available items that are accessible to designers at large, regardless of whether they have access to a laboratory or just to their own studio. The most important aspect of the photobioreactor is precise light control: we used an enclosed box, an outlet timer and full-spectrum LEDs. All these items were purchased from the local hardware store for the prices shown in Table 1. We used the outlet timer to program the LEDs according to the Dinoflagellates' circadian rhythm: 12 hours of light followed by 12 hours of darkness. As shown in Figure 3, the enclosed box ensured that the

material	quantity	cost (USD)
Pyrocystis fusiformis	200 ml	29.00
F/2 media part A and B	475 ml	25.98
Instant Ocean salt	6.8 kg	27.20
Distilled water	15 L	3.96
Full spectrum LEDs	1	13.99
Outlet timer	1	8.69
TOTAL		108.82

Table 1: Costs of starting a photobioreactor for Dinoflagellates

Dinoflagellates' circadian rhythm is not accidentally disturbed by the ambient light in the surrounding room.

Figure 3: Our photobioreactor built to host the growth of Dinoflagellates. The full-spectrum LEDs are precisely controlled by an outlet timer, providing 12 hours of light, and 12 hours of darkness according to the Dinoflagellates' circadian rhythm.

3.1 Growing and maintaining a Dinoflagellate culture

Lab-grown Dinoflagellate cultures are best started from a small culture, and overtime grown into a thriving, larger one. When in the process of *growing* the culture, designers should double the existing culture with the food medium (mentioned above), once a week. Once the desired culture size/volume is reached, designers should transition to *maintenance*; adding 30% of food medium, once a month. Preparing the food medium and feeding the culture is estimated to take up to 30 minutes each time.

Our starter culture was 200 ml of live Dinoflagellates which were doubled with food medium, once a week. After about 7 weeks our culture reached 20 liters and we transitioned to maintaining their health by feeding them only 30% of food medium once a month. In addition to feeding the Dinoflagellates, shaking and opening their containers once a day is essential for allowing gas exchange.

3.2 Quantifying bioluminescence for interaction

Bioluminescence is best experienced live in the dark, making it difficult to capture in a digital format such as photos (see Figure 1) and videos. To address this challenge, we further provide a series

of techniques that quantify the glow of Dinoflagellates, in terms of their illuminance, their light duration, and the glow color hue. For illuminance measurements we used the BT-881D Digital Illuminance Light Meter from BTMETER [6]. The instrument was held approximately 5 centimeters away from each environment while the Dinoflagellates were continuously stimulated to glow for approximately 10 seconds. We then recorded the maximum value over the 10 seconds. We repeated the measurement 3 times and calculated an average value. Figure 4a reports the average light illuminance (vertical axis) measured for three different types of interactive environments explored in this paper: (i) enclosed containers, (ii) porous materials such as foam and sponge sheets, and (iii) open environments (further elaborated in the Interaction section). As mentioned, to measure illuminance in these three scenarios, we had to continuously stimulate the Dinoflagellates. The closed environment was continuously shaken, while the porous environment was continuously brushed with a hand. For the open environment, we poured the Dinoflagellates into a bowl, and took measurements while continuously pouring. As seen in Figure 4a, the highest value of illuminance was measured for the closed environment (0.137 lux), while the porous materials presented the lowest illuminance value (0.033 lux). In comparison, a blue light emitting diode (LED) in the same dark environment emits 133.9 lux.

As mentioned, one of the affordances of Dinoflagellates is their ability to provide immediate feedback to physical stimulation through an instant and ephemeral glow. To determine the Dinoflagellates' glow duration, we analyzed our video recordings. Using a stopwatch we measured the time between from when the stimulation stopped until the glow disappeared completely. We calculated the average over three videos for each of the three environments explored in this paper. As shown in Figure 4b, the results show that Dinoflagellates in the closed environment can hold the glow for 2.66 seconds, almost three times longer than Dinoflagellates in the porous environment (0.89 seconds).

Figure 4: (a) The maximum light intensity emitted by Dinoflagellates in the three interactive environments explored in this paper. (b) The average time it takes for the Dinoflagellates' glow to dissipate in the three interactive environments explored in this paper.

In order to capture the specific hue of the Dinoflagellates' glow, we further analyzed the three videos in the open environment

(the environment that allowed direct filming, with no substrate in between the camera and the algae). For that, we isolated the light dissipation timelapse as described above (from the moment the stimulation ended until the glow disappeared completely). From that specific timelapse, we captured still images at 0, 0.5, 1.0, 1.5, and 2.0 seconds. We then used the color picker tool on Adobe Photoshop to determine the hexadecimal color value of the glow. We repeated the measurements three times (i.e., for three different videos) and calculated the average values. The results presented in Figure 5 show that the Dinoflagellates' light gradually weakens and dims over time.

Figure 5: Average color hue of the Dinoflagellates' glow captured every 5 seconds from the moment their stimulation ended to the moment the glow disappeared. We used the color picker tool on Adobe Photoshop to determine the hexadecimal color value of the glow (the average hex values are shown on top of each glow hue) from a video of Dinoflagellates in an open environment.

3.3 Interaction Mechanics

Dinoflagellates glow when the oxygen in their environment is increased. Given their liquid confinement, an increase in oxygen occurs through strong agitation. We translate this mechanism into *physical kinetic* interaction elements, based on physical and bodily movement (see Figure 6). However, to provide the necessary kinetic strength needed to trigger the glow, the movement has to be vigorous, steady, and consistent, similar to rocking a baby to sleep. Such interaction mechanics are very engaging, as in many cases the entire body is involved (to provide strength) and a specific rhythm (to stimulate and extend the duration of the glow, see Figures 4, 5). Thus, we explore movement that involves the entire body, such as shaking, hand-brushing, rocking, spraying, stirring, jumping, dancing, etc.

4 INTERACTION DESIGN

One of the most important questions we want to address with this work is how can designers establish boundaries when interacting and working with an organism. To achieve this, designers must overcome the limited means they have to assess the organism's own well-being and experience within the interaction. In order to consider the organism in the interaction, we step away from human-centered design approaches and introduce a framework that takes an *organism-centered approach* when designing interaction with living matter. We specifically propose starting from designing the environment for the organism, and only then proceeding to design the interactions within that environment. We present in the following section the components of the proposed framework, and

Figure 6: Schematic of the interaction between a human user and the Dinoflagellates. The feedback loop is activated by the human's physical action, followed by the Dinoflagellates' light as the visual feedback.

we further demonstrate in detail how we applied the framework to design physical kinetic interactions with Dinoflagellates (Section 4).

4.1 Framework

Researchers have previously speculated on designing with and for living matter, situating it as a design collaborator and equal partner [46]. In alignment with such approaches advocating for "more-than-human" design, we propose an *organism-centered framework*. We specifically focus on the environments where the organism can thrive and what interactions it affords. Thus, we approach the design process from understanding the appropriate environments for the specific organism and follow by exploring possible interactions within those environments. By doing so, we shift the attention towards the organism's needs, rather than on the desired outcome for the human user that may not take into account the organism's well-being. Our framework consists of four components (form, reception, feedback, and control) and uses the following principles and questions to guide designers in their design process:

- (1) **Form** - The *Form* component investigates the various shapes that the environment can take. In deciding the form factor, designers should consider the materials that the organism can thrive in, and whether the environment is natural or artificial. We suggest the following questions to assist designers in their exploration. What various shapes can this environment take? What materials can the organism live in? Is this a natural environment or an artificial one for the specific organism?
- (2) **Reception by the organism** - The *Reception* component aims to optimize the environment for the well-being of the organism. Specifically, the environment needs to accommodate the needs of the organism in terms of temperature, humidity, potential of hydrogen (pH), gas flow, and nutrients. We suggest the following questions to be answered. Can the organism thrive in this environment? How long would it take the organism to adapt to this environment? Is this environment stressful for the organism?
- (3) **Feedback** - The *Feedback* component is meant to assess the behavior of the organism within the designed environment. We emphasize the importance of incorporating means to capture the organism's response to the interaction within

the environment. We suggest the following questions to be answered. What are the available feedback abilities by the organism in this environment? What are the qualities of the organism's behavior (or response) when interacting with the organism within this environment? Can the feedback of the organism be perceived by the human in this environment? How long does it take the organism to respond or change its behavior once interacted with?

- (4) **Control/Action** - The *Control* component addresses the human user's actions and evaluates their potential impact on the well-being of the organism. We suggest the following questions to be answered. What actions can the human perform within this environment and do they harm the organism? To what extent can the human control the organism's response or behavior? How does the human interact with the organism in this environment?

4.2 Methods

We used brainstorming and bodystorming techniques [69] to design and test interactions with Dinoflagellates. We have been dedicated to taking care of our Dinoflagellates culture for over a year, allowing us to become very familiar with their needs and behavior. We experimented with maintaining our Dinoflagellates in different environments, testing their well-being in such environments over time, and interacting with them in each environment. In addition, we invited colleagues to witness the interactions in our lab space and shared recorded visual footage of the interactions. This allowed us to informally examine people's reactions to the interactions with the Dinoflagellates we designed, which sparked additional ideas for interaction. We determined the environment "successful" when the Dinoflagellates thrived in it (i.e., they survived for extended amount of time and weren't harmed during the interaction).

All our designed interactions are initiated by a physical kinetic stimulation of the Dinoflagellates, and the interaction output is the visual feedback of the Dinoflagellates' glow. As discussed in Sections 3.3 and 5, the nature of the Dinoflagellates dictated what interactions are possible; "technical" constraints such as the need for a liquid environment and specific temperature, their ephemeral quality, and the fact that Dinoflagellates are living organisms, all come into play when interacting with them.

4.3 Environments for Dinoflagellates

During our exploration, we found three environments effective in facilitating interactions with Dinoflagellates (schematically depicted in Figure 7: (1) closed environment, (2) porous environment, and (3) open environment). In the next subsections we discuss in detail each environment, and demonstrate how we applied the proposed framework to design physical kinetic interactions with Dinoflagellates. We also demonstrate such interactions with game examples that can help illustrate the opportunities and limitations of these interactions. To provide more insight into this experience, we also refer the readers to the supplementary video (<https://vimeo.com/541785261>).

4.4 Closed Environment

We explored interactions with Dinoflagellates contained in enclosed containers, such as the bottle in Figure 8. As presented in Section 3,

Figure 7: The three environments that facilitate interactions with Dinoflagellates: closed, porous, and open. We evaluate each environment from the organism’s perspective, and we further present interaction examples that satisfy the proposed design framework.

photobioreactors, commonly found in controlled laboratory settings, can regulate and control the organism’s environment, which helps avoid external contamination. Since any design work with living matter would require maintenance of the culture in a controlled environment (see photobioreactor in Figure 3), a good starting point for designers is to work directly with a version of the artificial home of the organisms.

In the following paragraphs we evaluate and analyze the use of closed environments for designing interactions with Dinoflagellates, following our framework presented in Section 4.1: form, reception, feedback and control.

Figure 8: We explored interactions with Dinoflagellates contained in enclosed containers, such as a plastic bottle. When physically interacting with Dinoflagellates in closed environments, their glow will appear *concentrated* and will reflect the strength of the Dinoflagellate culture.

Form. Containers of various shapes can be used as a closed environment for Dinoflagellates, e.g., transparent bottles (see Figure 8), bags, tubes, and custom-made containers. However, regardless of the shape, the container should be waterproof (to hold the algae) and transparent (to allow light absorption for photosynthesis). Moreover, the Dinoflagellates’ glow will not be visible in an opaque container. Examples of materials that can provide the needed transparency, include silicone, acrylic, plastic, Polyvinyl Chloride (PVC), and glass. To create rigid container shapes, we prefer using heat-resistant glass because it can be properly sterilized (autoclaved under pressure). For soft container shapes we prefer using heat-resistant plastic sheets that we sterilize and then seal as bags using thermo-adhesion. With any enclosed container, designers should keep the container 3/4 full in order to allow gas exchange at the surface (as explained in Section 3, Dinoflagellates consume CO_2 and release O_2).

Reception by the organism. Dinoflagellates can thrive in transparent enclosed containers for long periods of time, e.g., our cultures have been alive for more than 16 months in the same enclosed containers. We strongly encourage building interactions within a closed environment since it aligns with the traditional procedures of maintaining Dinoflagellates cultures in a laboratory setting [10, 66].

Feedback. When physically interacting with Dinoflagellates in closed environments, the light produced will appear *concentrated* and will reflect the strength of the Dinoflagellate culture. The measurements presented in Figure 4 show an illuminance of 0.137 lux and glow duration of 2.66 seconds for our Dinoflagellates kept in enclosed containers.

However, like every living organism, Dinoflagellates have a limited capacity and tolerance of resources. Designers should keep in mind that while physical stimulation by movement is essential for their survival, Dinoflagellates won’t produce light after *repeated* physical stimulation. Depending on the health and strength of the culture, Dinoflagellates will produce light for a limited amount of time of physical stimulation and will stop in order to recharge. We consider Dinoflagellates’ ability to produce light as an immediate and ephemeral feedback to be one of their affordances, and discuss the challenges around time and temporality in Section 5.

While the ephemeral quality of the Dinoflagellates’ glow is visually compelling, it makes it difficult to document in digital format. Unfortunately, the figures in this paper can not fully capture the experience of these interactions. To provide more insight into this experience, we refer the readers to the supplementary video (<https://vimeo.com/541785261>).

Control/Action. The human user has “binary” control over the light production of Dinoflagellates. In the absence of movement, Dinoflagellates will stay still, but once an external source of movement is introduced, they will produce light. Essentially, whenever physically stimulated, Dinoflagellates will produce light (binary 1 or ON), and when static, they won’t (binary 0 or OFF). The enclosed containers can be held and stimulated by the users’ hand movement, carried on the body and stimulated by the users’ body movement, or stimulated by an external movement “source” (e.g., piezo components). We consider directly moving a container containing the Dinoflagellates to be a *direct interaction*, where the human user’s movement is directly coupled with the feedback of the organism seen as the light produced. When the light produced by the Dinoflagellates weakens or there is no longer light produced with every movement, the human user should pause physical stimulation and allow the Dinoflagellates to recharge.

4.4.1 Example. We illustrate the interaction with Dinoflagellates in a closed environment, through the means of a checkers game (see Figure 12). We used fluorescent tape to mark the checker board (to be visible in the dark) and sterile petri dishes as checkers. The petri dishes (**Form**) were filled with Dinoflagellates and sealed with Parafilm tape. Petri dishes are sterile transparent containers commonly used in laboratories, thus a good environment for the organism to thrive in (**Reception by the organism**). Whenever a player makes a move and places the checker in a new position (**Control/Action**), the checker will glow (**Feedback**) and mark the new position.

Figure 9: Example checkers game using Dinoflagellates in closed environments (a) in ambient light and (b) in darkness. As checkers we used sterile petri dishes filled with Dinoflagellates and sealed with Parafilm tape. Whenever a player makes a move and places the checker in a new position, the checker will glow.

4.5 Porous Environment

Dinoflagellates can also be "contained" in porous environments (e.g., sponge and foam materials), see Figure 10. These materials can absorb the Dinoflagellates medium, containing them in the pores of the material and on the surface.

Figure 10: We explored interactions with Dinoflagellates contained in porous environments such as a foam mattress. This environment can be experienced as a "responsive" surface that echoes any touch it comes in contact with.

Form. Porous materials, such as sponges or foam, will allow Dinoflagellates to "hide" inside of them when poured on the material or soaked inside (see Figure 10). Such environments can be easily customized by simply cutting them into the desired shape. As mentioned earlier, ideally designers will choose heat-resistant materials as they can be properly sterilized to avoid cross-contamination. Transparency is not a requirement for porous environments, as the Dinoflagellates lay on the surface of the material thus coming in direct contact with the ambient light for photosynthesis. In the following paragraphs we analyze the use of the porous environment for designing interaction with Dinoflagellates, following our framework presented in Section 4.1. Specifically, we evaluate the porous environment for Dinoflagellates following the four components of our framework: form, reception, feedback and control.

Reception by the organism. While sponges and foam surfaces can "hold" the Dinoflagellates, they are neither sterile enclosure, nor their natural environments. Given that, we had concerns if Dinoflagellates can thrive in porous environments. Our experiments showed that if kept moist, Dinoflagellates can live inside these

materials for extended periods of time. Specifically, we placed the Dinoflagellates' infused sponges in sealed bags and stored them in the photobioreactor. We checked the Dinoflagellates cultures daily, and they keep on thriving even after a week of being in a porous environment.

Feedback. The visual quality of the light produced by Dinoflagellates in porous surfaces is more subtle in comparison with the light intensity of Dinoflagellates in closed environments. The measurements presented in Figure 4 show an illuminance of 0.033 lux and the glow duration of 0.89 seconds for our Dinoflagellates kept in porous environments, resulting in a glow four times less intense and twice shorter than in closed environments. This happens because a lot of the Dinoflagellates are soaked inside the material, and thus their glow weaker.

Control/Action. This environment can be experienced as a "responsive" surface that echoes any touch it comes in contact with (see Figure 10). When interacting with Dinoflagellates in porous materials, the human has more "control" over the light produced. As opposed to closed environments where the whole container lights up when stimulated, porous surfaces will light up only where touched by the human and according to the intensity of the gesture. If the material is lightly brushed by the human's hand, the visual effect will resemble a light glittering glow, and if the gesture is more aggressive (e.g., tapping the material, pressing down), the Dinoflagellates will emit a stronger glow that will last longer. The same porous surface can also be sprayed with the Dinoflagellates medium, and can result in a "spray painting" interaction with the light produced by the Dinoflagellates (see Figure 11). Once again the ephemeral quality is evident since contact with the porous surface will cause it to "light up", however it won't last long before it disappears.

Figure 11: Spray painting with Dinoflagellates on a porous surface. Dinoflagellates were placed in a pressurized spray bottle and sprayed onto a porous surface. The spraying results in a glittering light effect on the porous surface.

4.5.1 Example. Porous materials can be used for contact-games as they glow when touched. For example, a game of hopscotch can be played with hopscotch squares made out of a sponge surface (**Form**) and soaked in the Dinoflagellates medium (see Figure 11). Players jump (**Control/Action**) in the empty squares and balance

on one foot in the single squares. If a player's jump doesn't manage to light up the square (**Feedback**), they start over. As explained above, Dinoflagellates can survive in porous materials over time (**Reception by the organism**). Since the medium has very high saline levels, direct contact with microbes from the human body have very low chances of survival and contaminating the culture. Some of the Dinoflagellates, however, may be left on the human's skin.

Figure 12: Hopscotch with Dinoflagellates in a porous environment. Players jump in the empty squares and balance on one foot in the single squares. If a player's jump doesn't manage to light up the square, the players start over.

4.6 Open Environment

Human users can directly touch and manipulate the Dinoflagellates medium by hand. This would include pouring, and mixing the medium in an open container, directly stimulating it by hand. In the following paragraphs we analyze the use of the open environments for designing interaction with Dinoflagellates, following our framework presented in Section 4.1. Specifically, we evaluate the open environment for Dinoflagellates following the four components of our framework: form, reception, feedback and control.

Figure 13: We explored interactions with Dinoflagellates in open environments such as a bowl. The light produced by Dinoflagellates in open environments visually resembles the light they produce in their natural environments: ocean waves containing Dinoflagellates have a subtle, ambient ripple of light.

Form. Wide, open containers and surfaces can be used as open environments for the Dinoflagellates (see Figure 13). This environment best simulates the Dinoflagellates' natural environment, and can be replicated in a controlled setting. Material transparency in open containers is not a requirement, since the large surface area allows direct light transfer for photosynthesis.

Reception by the organism. Dinoflagellates are found naturally in large *open environments*, such as oceans and seas. However, in artificial open environments, Dinoflagellates will not thrive after long periods of time if not correctly maintained to avoid cross contamination. Thus, after spending time in an open environment, Dinoflagellates may be sealed or placed back in closed containers and in their photobioreactor. In addition, if designers are interested in maintaining Dinoflagellates after directly interacting with them in an open environment, they should strive to keep the Dinoflagellates medium as clean of contamination as possible. Gloves and sanitation measures can be taken in order to maintain the medium.

Feedback. The light produced by Dinoflagellates in open environments resembles the light they produce in their natural environments. The ocean waves containing Dinoflagellates have a subtle, ambient ripple of light, which can in an artificial open environment. The intensity of their glow is in between the values measured for the closed environments and the values measured for the porous environments. Specifically, the measurements presented in Figure 4 show an illuminance of 0.087 lux, and a glow duration of 2.35 seconds for Dinoflagellates kept in open environments.

Control/Action. Similar to the human's control when interacting with Dinoflagellates in closed environments, the control is "binary". Whenever stimulated, the Dinoflagellates medium will produce light, and whenever calm without movement, the medium will remain still and without light. However, open containers and surfaces allow the human to directly touch the Dinoflagellates medium, directly stimulating them by stirring, pouring, splashing, or simply moving the medium. Open containers and surfaces also allow to submerge external objects into the Dinoflagellates medium, which can also stimulate light production. The following interaction example demonstrates this.

Figure 14: Example ball game with Dinoflagellates. Each player is shooting four ping-pong balls into a bowl containing Dinoflagellates, obtained one point for each scored ball. Each player gets one last chance to win five points if they score using a lacrosse ball.

4.6.1 Example. The Dinoflagellates medium can be poured into an open container (e.g., a transparent bowl as the **Form** of the environment) and act as a "basket" for a ball game (see Figure 14). Players can aim throwing the ball (**Control/Action**) into the bioluminescent basket and receive the glowing **Feedback** when they manage to get the ball in the bowl. When players finish playing the game, the container can be closed or the medium can be poured into a closed container for storing the culture back in the photobioreactor (**Reception by the organism**).

5 DISCUSSION

In this paper, we propose a framework for designing interactions with living matter, with the aim of shifting the design perspective towards an organism-centered approach. We demonstrate this framework by exploring physical kinetic interactions with Dinoflagellates. In line with recent design approaches that call for "more-than-human" design practices, our framework positions living organisms as more than just *matter*, but as an *active entity* [35] to consider as part of the design process. Positioning the organism as an active entity, attempts to decentralize the human, shifting the traditional focus of human-centered design to a more holistic practice [71]. We further argue that a holistic design practice with living organisms can only be achieved in organism-centered approaches that focus on the ideal conditions for the organism to thrive and allow a relationship between humans and the organism. We acknowledge the limitations of this approach (see Sections 5.1 and 5.2), as a truly collaborative and mutual beneficial interaction between the organism and the human user has to overcome the challenge of assessing the *experience* of the organism.

Aiming for a more organism-centered design approach brings attention to thinking of the needs and well-being of the organism, and understanding the interaction and design opportunities that stem from a thriving relationship. In this work, we specifically address this by focusing on the environments preferred by the organism; thus first establishing boundaries and design constraints based on the comfortable environment of the non-human organism, and only then proceeding to explore the available interactions within those environments. Perhaps this practice reinforces non-anthropocentric design thinking [13], especially considering that the design medium is a dynamic living entity, as opposed to non-living electronic components and static materials.

Such a design process can also take a more sustainable standpoint, another goal in non-anthropocentric design thinking. Design practices such as life-centered design [44] and nature-inspired design [14] aim to promote sustainability from the perspectives of materiality, product life cycles, and how products are situated in communities and in the world, for present and future generations. The approach we propose in this paper specifically addresses designing with living matter. The approach calls for considering the well-being of all biological entities involved in the design practice and interaction, first stemming from understanding the needs of the living matter (which are usually overlooked), and then proceeding to unfolding the opportunities for human interactions within that space. Taking into account the needs and well-being of all biological entities involved can promote an overall more conscious and aware design practice, leading designers to consider the enlarged scope of social responsibility and ecological awareness.

As designers continuously attempt to create *meaningful* interactions, we believe that a "symmetrical" interaction between the human and the organism can account for an interaction that stands beyond just delight or satisfaction, and towards the notion of "life as a shared experience" [1, 35, 51, 60]. Our framework emphasizes and prioritizes the livingness quality of the organism and the importance of considering the well-being of the organism in order to design interactions that hold *life* at the center of the experience.

Our exploration of interactions with Dinoflagellates has a strong physical component motivated by the fact that direct kinetic and bodily interactions hold potential for intimate experiences [19, 30]. Our constant interaction with Dinoflagellates during our exploration made us realize that embodied interaction with living media can be experienced in a fundamentally different way than with non-living media [51], presenting an opportunity for designing systems and interfaces that closely couple human users and living media. Moreover, such physical kinetic interactions can embody a somaesthetic [70] relationship between humans and the living matter and further raise kinaesthetic awareness [9] in the human user's movement and ability to affect the world.

5.1 Ethical Concerns

Since designing with *living* matter is an emerging research domain that involves life, it is essential to bring attention to the ethical concerns around the well-fare of the non-human organism. Given a long history of using animals as pets and the consequent connection that forms between the human owners and their pets, such ethical discussions occur mainly in the context of designing with animals [47, 48, 76]. The situation is different when using micro-organisms in design. Known as microbes, micro-organisms tend to instigate fear, disgust, repulsion, and a strong desire to have them removed from our environments. Such anti-microbe feelings have been recently reinforced by the covid-19 pandemic. In spite of this, we strongly believe in the importance of raising ethical concerns around using life (even as micro-organisms or as DNA) as a material. While not widely discussed in design research, this topic has deeply engaged the arts community, thus inspiring various art installations, and performances [50, 72].

A central challenge when designing with micro-organisms, is the lack of direct communication between the microbes and the human user. It is difficult to assess how the microbes perceive the interaction, their experience using the interface, and their well-being within the system. Such assessments can be made after thorough research of the organisms, i.e., the designer needs to engage with specialized literature in biological sciences to learn about the optimal thriving conditions for the microbe. Based on this knowledge, the interaction environment can be designed to accommodate the needs of the microbe in terms of temperature, humidity, potential of hydrogen (pH), gas flow, and nutrients. We present such an approach in this paper (see Section 4); we specifically propose focusing on designing an organism-centric environment, and then base the interaction design on that environment. This approach shifts the designer's perspective from using any means to precisely control the organism so that the desired goals are achieved (e.g., trapping *Euglena* and *Volvox* [39, 45]), to rethinking the interaction around the well-being of the organism.

Some organisms present characteristics and reactions that are in the human sensory spectrum, and thus can be incorporated in the interaction design to capture the well-being of the organism. Examples include Dinoflagellates that glow when shaken, and bacteria that grows in visible line patterns [78, 79]. Less researched are interactions based on olfactory sensations, since they require a long-term interaction with the organism for the user to become familiar and aware of the microbe's specific smell. In our practice,

we regularly assess the health of the organism cultures by using microscopy or photo spectrophotometry; however, we acknowledge that a majority of designers or HCI researchers may not have access to such laboratory equipment.

Last, our desire to explore direct (kinetic and physical) interactions with Dinoflagellates is strongly motivated by ethics and our concern with the way microbes are perceived by the human user. We hope that interactions with the human user physically engaged with the organisms, can help the human user become more aware of the livingness of the organism, and be more considerate towards life, in any form it may take. This should be further studied and addressed in future work with living matter. In addition, future work should explore and produce further kinetic and embodied design practices and interactions with Dinoflagellates, and living matter in general.

5.2 Challenges and Limitations

Our work introduces Dinoflagellates and their bioluminescence as active components in a direct interaction model. Designing with Dinoflagellates presents a series of challenges, such as the need for a dim surrounding, synchronizing with the algae's awake time, and a large space to allow vigorous and rhythmic movement. As living organisms, Dinoflagellates need constant care (see Section 3) and are in danger of contamination with blue-green algae (cyanobacteria). In terms of care and maintenance Dinoflagellates must be "contained", they require a temperature between 18°C and 22°C, and they need a programmed light source to correspond to their circadian rhythm. Moreover, the exact mechanism we explore for interaction (bioluminescence triggered by movement) affects the portability of Dinoflagellates: after being constantly moved during transportation, they are severely depleted and need 1-2 days to recover.

Designing for bodily interaction in the dark presents its own challenges, as the lack of visual guidance leads users to base their decisions on a wide range of emotions, from fear of the unknown to blissful ignorance [75]. In this work we use the Dinoflagellates' light as an opportunity for designing in the dark with the affordance of an immediate visual response to the human user's physical actions. In spite of the visual feedback from the bioluminescence, we still had to consider the safety of our interactions and take extra measures to arrange the surroundings.

In this paper, we focus on providing tools, methods, and a framework that will guide designers in further developing interactive living systems. While we briefly present a few examples of how such interactions can be used in the context of working with Dinoflagellates, we acknowledge that our work only scratches the surface in terms of the many opportunities living media provides. We hope our work will encourage the design community to further explore physical and direct interactions with living matter.

6 CONCLUSION

We explore direct and physical kinetic interactions with Dinoflagellates (bioluminescent algae) and approach the design process from an organism-centered approach. To this end, we present a framework meant to direct designers towards considering the well-being and needs of the organism, by focusing first on designing

appropriate environments for the organism and following by exploring the available interactions within these environments. In accordance to our proposed framework, we present three environments appropriate for Dinoflagellates, the possible interaction for each environment, and provide real-life examples for each environment. We also discuss how an organism-centered approach can shift design practice from human-centered design towards a more holistic design practice and decentre the human. Finally, we bring attention to the main ethical concerns around designing with living matter. Through this work, we aim to inspire designers and HCI researchers to explore physical and direct interactions with living matter, with Dinoflagellates in particular, while considering the well-being of the living organism.

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