“Turning the Invisible Visible”: Transdisciplinary Bioart Explorations in Human-DNA Interaction

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Hybrid interactive systems that combine living and digital components can engage, educate, and inform users, and are of growing interest in the HCI community. Advances in synthetic biology are transforming what is possible to do with these living media interfaces (LMIs). Bioart is a practice in which artists, often using synthetic biology methods, work with living organisms to creatively explore the human relationship with nonhuman organisms. We present results from an interview study with expert bioartists as well as our hands-on experience in a bioart project where we created poetry-infused wine by encoding and inserting a Persian Sufi poem into the DNA sequence of living yeast cells. We find that engaging in bioart practice generates transdisciplinary fluency with implications for access and activism and our understanding of the qualities of living media. We further explore the qualitative aspects of interacting directly with DNA and implications for sustainable futures.

CCS CONCEPTS • Human-centered computing • Human computer interaction (HCI) • HCI theory • concepts and models

Additional Keywords and Phrases: Living organisms, bioart, transgenic art, DIYbio, community science, biotechnology, synthetic biology

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1 INTRODUCTION AND BACKGROUND

The Human-Computer Interaction (HCI) research communities are continuously reflecting, investigating, and re-defining what it means to interact with computational systems [25], [37]. While the majority of this endeavor has focused on interaction with digital systems, an increasing recognition of the social, material, and environmental aspects of HCI necessitate the development of transdisciplinary perspectives and lenses for interrogating our relationship with technology beyond a focus on the digital [8][9][25]. While HCI is inherently interdisciplinary and is built on diverse perspectives and epistemologies from multiple fields [32], it is not yet informed by contemporary artistic perspectives on what it means to engage and interact with nonhuman living organisms and the environments in which they live. These perspectives can provide inspiration for re-thinking our place in and relationship with the world, and insight into both the creation and interrogation of emerging interactive systems that incorporate living organisms [56].

Blevis and Stolterman [10] defined the purpose and potential of HCI work in a transdisciplinary mode as that which pursues socially relevant outcomes by drawing on "collections of methods and their associated domains of expertise" with the goal of transcending the demands of disciplinarity [10]. However, methods and outcomes related to this form of inquiry are infrequently reported, limiting the potential to address significant ecological and social challenges. We argue that engaging with bioart offers opportunities to HCI researchers and practitioners who are looking to begin working in a transdisciplinary mode (i.e., with a focus on ecological and social needs rather than disciplinary advancement) [9]-[12][63][64]. Our findings also provide insight for those looking to engage with emerging media and technologies such as living organisms and synthetic biology in an interdisciplinary mode. Bioart can be understood in the tradition of "new media," a space for exchange between technologists and artists advancing understandings of ethics and aesthetics in cultural production [23], [55]. Our findings underscore the value of working together with artists, whose work focuses on social critique and cultural production, and who tend to aspire to transdisciplinary modes of collaboration [31].

Bioart (aka *BioArt*, *bio art,* and *biological arts,* among others) is an art practice whereby artists work with living organisms, including animals, plants, fungi, microorganisms and others, for artistic and creative purposes [7], [43], [58]. While bioart emerged in the beginning of the 20th century, a range of factors have contributed to its prominence as a thriving art movement including advances in synthetic biology (a life science research area focused on genetic engineering, tinkering, and systems biology and concerns about its consequences [71]), recognition of bioart as a distinct contemporary art movement at prominent institutions such as the Museum of Modern Art (MOMA) [59] and the Ars Electronica Festival [4], and the creation of numerous DIYbio amateur communities that strive to increase "public participation in biology outside of professional laboratory settings" [48]. Hackteria—an open-source DIYbio organization with a focus on integrating science, technology, and art, provides an example of the transdisciplinary potential that can occur at these intersections [33][54]. Additionally, achievements in the similar field of *biodesign* have motivated a broader interest in interdisciplinary collaborations with biologists [60][72]. Biodesign is similar to bioart in that it borrows inspiration, materials, and procedures from biology, but pursues practical and instrumentalized aims through the creation of products and services.

A significant body of bioart has emerged since the beginning of the 20th century. We refer the reader to books that catalogue and critique important works in this area [7][58], [61], and in the current paper briefly describe three canonical examples of bioart projects. In *Nature?* (2007) Marta de Menezes modified the wing patterns of living butterflies without modifying their genes [22]. This work resulted in the creation of patterns never before seen in nature that are not transmitted to the next generation of butterflies and thus, in the words of the artist, are "artworks that literally live and die. They are an example of art with a lifespan—the lifespan of a butterfly." In *Natural History of the Enigma* (2003-8), Eduardo Kac merged his DNA with that of a petunia plant such that the plant's veins in its leaves were turned red, mimicking the flow of blood through human veins [40]. Finally, in

Bacterial Radio (2012), Joe Davis created a crystal radio by using biomineralized *Escherichia coli* (*E. coli*) bacteria as inductors and capacitors embedded in silicone [20]. An aim of the project was to demonstrate a less resource intensive and polluting way to create information receptors.

While we have chosen to primarily use the term "bioart" in this paper (except when participants preferred otherwise), although the term is currently debated and there are several others (e.g., biological arts, hybrid art, and transgenic art, among others) in use by artists [58][61]. Additionally, genetic is only one form of manipulation techniques employed by artists to work with living organisms [17], [56]. We view both these features as being indicative of the vitality of the field and ongoing dialogue about its identity and purpose.

Recent research has explored the intersection of HCI and bioart by undertaking hands-on projects [3][48], [47] and developing meta-analysis of bioart and biodesign perspectives [56]. In this paper, we contribute to the conversation between HCI and bioart by presenting results from an interview study with expert bioartists in which we asked the artists about their perspectives on working at the intersection of biology and art, followed by a first-hand account of our interdisciplinary team's experience with conceptualizing and conducting a bioart project in a DIYbio lab. Results from the interviews show how engaging in this practice requires and generates transdisciplinary fluency, identifies specific characteristics of living organisms in artworks that humans perceive and relate to, and describes how bioart's activist orientation can negotiate access to social and material resources. The presented bioart project shows practical steps of translating and storing units of textual information in the DNA of living organisms using DIYbio materials and procedures accessible to non-experts and provides an account of how non-experts may interact with the DNA of living organisms using contemporary synthetic biology mechanisms. We use our findings and reflections to inform a discussion about the possibilities of mutual transdisciplinary collaborations and conversations between bioartists and HCI experts. We further reflect on how bioart can provide insight into the role of humans and their relationship with technology at a time of ecological and social crisis and discuss practical opportunities and concerns related to the instrumental use of living organisms for interactivity. We envision the contributions of this paper as twofold: first, to inform the design of transdisciplinary conversation and mutual learning initiatives combining biological material and techniques, artistic ideation and critique, and interactive system design and evaluation; and second, to stretch the boundaries of materials and methods considered in design, inspiring the creation of hybrid interactive systems that include nonhuman living organisms and are situated at the intersection of bioart and HCI.

2 RELATED WORK

There is a small but growing body of research in HCI that investigates the possibilities of working with living organisms through the design of interactive artifacts [30][34][49][76], the creation of tools and processes to create novel hybrid systems [30][76], and studies with DIYbio communities [46]-[48][52]. In a recent review of living media interfaces (LMIs), interfaces that combine living organisms and digital components, Merritt et al. used four lenses, biological, ethical, artistic, and HCI, to analyze a series of exemplar interactive projects that combine living organisms and digital components [56]. They described a range of work in this interdisciplinary space, a space that has primarily focused on the functional and design-focused aspects of working with living organisms, and these aims are in line with research and practice in the field of biodesign [61].

Many examples of recent work in HCI have investigated the possibilities of incorporating living organisms in interactive systems. We describe three here. *Infotropism* consisted of a corn plant placed between two directional lights, one corresponding to a trash bin and the other a recycling bin [38]. The corresponding light would turn on whenever a bin was used, causing the plant to respond to the light and lean towards the more used bin over time. In *Babbage Cabbage*, the color of cabbage plants was manipulated by changing the pH level of a solution in which they were placed to reflect different values of statistical data dynamically collected from the Web [28]. Finally, in the *Trap It!* museum installation, users could view *Euglena gracilis* microorganisms through a magnifying glass and interact with them through a touchscreen and optical hardware [49].A few recent projects have specifically focused on exploring the intersection of bioart and HCI, viewing bioart as a site of cultural production and interrogation that through its material entanglement with both digital and biological entities may open up new opportunities for interdisciplinary discussion. Alistar and Pevere created a tangible bioart installation that embedded the memories of an elderly participant that were recorded, transcribed and encoded into DNA code before being inserted into the cells of *Komagataeibacter rhaeticus* bacteria [3]. In addition to describing their process of encoding text information into the DNA of living organisms, the authors discussed the characteristics of living organisms as tangible living media that, in comparison with digital physical computing components, may create a sense of relatability in human audiences and provide opportunities for rapid replicability (through cellular reproduction), as well as having a slower response time and increased chance of contamination. The authors encourage further explorations in this area and identify the need for interdisciplinary collaboration and domain knowledge exchange as both a challenge and opportunity for the HCI community.

In another project, Kuznetsov et al. presented an autoethnographic study of the process of transforming a university HCI lab into a BSL-1 (biosafety level 1) DIYbio facility and organizing a weeklong bioart workshop for youth [48]. During the workshop, youth created microbial art (also known as Agar Art [2]) by using creative stencil outlines as templates to transfer living microorganisms that express colors to lab plates containing a growing agent (i.e., microbial growth media hardened with agar). The authors observed that interacting directly with living materials afforded “new ways of seeing” and made the youth aware of a certain form of nonhuman agency in how the living organisms responded to each other and other materials used in the workshop over time. In another project, Kuznetsov et al. explored the possibilities of several pieces of existing and customized biology lab equipment, including an OpenPCR and a Pearl Blue Transilluminator (tools for amplifying and visualizing DNA, respectively), for engaging non-biologist members of the public in DIYbio prototyping and exploration [47]. They found these platforms to be effective tools for collaborative knowledge production and found DIYbio itself as a site for public engagement with science. Findings from these projects echo previous research outcomes that have both shown the learning value of engaging in bioart and biodesign activities [1] and identified parallels between hands-on digital making and DIY activities and DIYBio practices [44][73].

The current project contributes to this space by both presenting the perspectives of expert bioartists on the possibilities and challenges of future hybrid interactive systems that may incorporate living organisms as part of their design, and also presents a first-hand account of a project that falls in the intersection of HCI and bioart by investigating how researchers and practitioners may interact with the DNA of living organisms through state-of-the-art DIYbio methods. We present methodological opportunities for engaging in transdisciplinary modes of work in HCI in the emerging space of interaction with nonhuman living media.

3 BIOARTIST INTERVIEW STUDY

3.1 Interview Study Methods

3.1.1 Participants

We interviewed 6 expert artists currently working with living organisms in their practice. Their choice of living media is diverse and includes plants, animals, fungi, microorganisms, and biologically derived molecules. Their duration of experience working in bioart is difficult to quantify due to the nature of encountering living organisms as media, with an average of about 7 years. Our sample includes diverse age and gender perspectives but lacks diversity of race or ethnic identity. See Table 1 for participant demographic information. All but one participant (P5) are currently based in the United States. They have diverse educational backgrounds, including both formal and informal training in the biological sciences. This sample of bioartists was recruited using a combination of community connections, online searches for local artists, and snowball sampling.

Table 1: Participant demographic information

Participant	Name	Age	Gender	Race/Ethnicity
P1	Carolyn Angleton	50s	Female	White
P2	Stephen Bradley	60s	Male	White
P3	Mary Maggic	20s	Non-binary	Asian
P4	Ryan Hoover	40s	Male	White
P5	Anonymous	30s	Female	Declined to say
P6	Lisa Moren	50s	Female	White

3.1.2 Data Collection and Analysis

We conducted in-depth, semi-structured interviews lasting between 48 and 78 minutes. We asked participants about their artistic practice, motivations for working with living organisms as media, the role of digital technology in their work, and possible future directions for bioart and the use of living media. We obtained Institutional Review Board (IRB) approval for the study prior to data collection. Our IRB approval included permission for publishing participants' names, if requested by them since they discussed their professional creative practices. Five of the 6 participants gave permission for their names and affiliation to be shared. The interview protocol was piloted with two participants to refine questions and flow. Interviews were conducted in person and through videoconferencing. All interviews were audio recorded and transcribed using a combination of automated and manual transcription.

In this study, we took an inductive approach to the data, interrogating both participants' experiences and the broader discourse around biology, art, and digital technology. We used open and axial coding and memo writing [19] to develop multifaceted themes. We used reflexive thematic analysis [14] [15] in order to suggest actionable starting points for inquiry into more-than-human HCI and in particular, the design and evaluation of LMIs. This process resulted in eight categories integrated to inform three themes that most closely relate to the subject of the current paper: *bioart generating transdisciplinary fluency*, *the familiarity of living media,* and *negotiating access*. On reviewing the literature, we found these themes to be united by a central concept of transdisciplinarity.

3.2 Interview Study Findings

3.2.1 Bioart Generating Transdisciplinary Fluency

Participants described how the process of drawing on skills from multiple fields or working with collaborators with diverse technical and epistemological backgrounds can generate transdisciplinary knowledge. We observed that many participants remained "in character" as artists during the interview while others at times—or even most of the time—appeared to take on a scientific perspective in the process of speaking about their work and experience in bioart. This ease of switching between perspectives seems to signal a sense of fluid disciplinary identity. For example, P1 described her and her collaborators' process in scientific terms while also considering artistic aims:

> "[W]e're doing a project that's called rendering a biosynthetic carotenoid pathway. And what we're trying to do—what I was interested in—is how to create color changes to biological events. And so, a carotenoids pathway is a metabolic pathway found in plants and it's what makes an orange pigment, like in a carrot or in fruit, this kind of thing. And there's a series of steps of different genes that have to be synthesized along that pathway. And so, I wanted to develop an art piece that was in effect a biosensor, a meter of whether the genes had been synthesized. … We're trying to do it in *E. coli* and we're working with designing the genetic constructs to create the different steps of that pathway. And rather than doing that through BioBits that are available, we're trying to construct them ourselves."

We use the term *transdisciplinary fluency* to describe the comfort transcending disciplines that we saw connected to a broader transdisciplinary attitude. Transdisciplinary fluency may emerge from hands-on practice and study with living organisms. Some of the artists we interviewed spoke of a desire to become competent in the lab. For example, P4 described the need for direct experience in his journey using both digital and living media to critique culture: "I found that you can't really do that critique from the sidelines. One, nobody really wants to listen to you from the sidelines. And two, you're often operating from an uninformed position if you're not really involved in the technology." P4 is an instructor at an art and design college, and also spoke of establishing students' technical foundation in the lab before pursuing artistic projects fully. Despite achieving fluency, according to our participants, bioartists do not need the same level of training or experience as scientists. P1 said, "as an artist in terms of whether you're doing cutting-edge research, I'm not sure that you always are. I think you're less likely to do that than actual scientists who have been trained in that. But I think you can intersect and have conversations with scientists in a way that enlightens and kinda ask things from a different perspective." P5 offered another reason to seek balance in transdisciplinary work: "you don't need to just spend all your time in lab, … because, also, for you, it's important to have [artistic] content."

All of the artists we interviewed described a fascination with and intimate understanding of living media that grew through intensive study, such as viewing through a microscope, growing specimens, and observing natural processes. Simple but close study of living media and organisms led to artists' desire to manipulate form as well as other artistic ideas. For example, working on a bioart project for P4 can involve, "just doing a lot of direct observation and looking out the window at the oak tree in my neighbor's yard and trying to script [i.e., code] this."

While most of the artists we interviewed conduct most or all of their biology work in a lab setting, two (P1, P2) described working in mixed or primarily field settings. P2, who studied biology at the undergraduate level before switching to fine art, described his early attempts to gain proficiency in the lab: "I was learning DNA sequencing, or going through the exercises of it. And it's the same reason why I dropped out of science in the beginning is I really want—I'm a field person; I love being outside, I like being part of the ecosystem." However, P2 described the same intensive, hands-on study of living media that lab-based bioartists describe: "I'm interested in knowing more about the mussel and its whole structure, how it filters the water with these kind of eyelash kind of structures, and also the oyster itself, it's circulatory system. So, by understanding those systems maybe I could build an artificial oyster that does something."

While most of the artists we interviewed spoke of scientists as limited by the constraints of their discipline, half of the participants (P1, P2, P6) acknowledged getting creative and artistic input from their scientific collaborators or spoke of their collaboration as having a shared creative vision. For example, P6 described a project in which she wanted to create sound using the DNA of a microorganism so that the vibrations would stimulate the organisms' bioluminescence. She asked her marine biologist colleague, "Can you give me some DNA pattern and I'll output it to music?" and then described how, "what he picked out was the part of the DNA of these guys that creates bioluminescence." This artistic choice by the biologist colleague aligns with P6's overall collaborative experience.

While none of the bioartists we interviewed work alone, their work styles represent a range, including working primarily independently. All of our participants who regularly work closely with biologists spoke of generative collaboration. Several participants described scientists broadly as confined or limited by their discipline. Speaking about the ethical issues their work interrogates, P3 stated, "I have lesser expectations for a scientist because I know in that kind of scientific field and the way that the scientists are socialized, I feel like they would think that, only to check a box or something on the list of things you should ethically do. … I just felt like the scientific field doesn't have a lot of freedom." P1 and her biotechnology colleagues are working on improving interdisciplinary collaboration:

> "We have set out, probably for about two and a half years now, trying to do lab-based art projects that look at ways to develop protocols, develop curriculum and develop actual, high level, professional interactions. Interactions between highly trained people in each field. So, part of it is aimed at access and teaching in terms of what's going on at a community college level or a community-based lab. But it's also aimed at how do you develop a methodology for interaction between professionals from different fields?"

All participants spoke about how transdisciplinary fluency generated through bioart practice helps them make contemporary issues about biology, ecology, and/or biotechnology accessible and meaningful to the public. Participants described learning "about the public and what they're capable of comprehending" (P2) through trial and error, and they use their commitment to transdisciplinarity to meet audiences where they are. For example, while P3 makes a living by exhibiting their work in galleries, they say: "to be honest, I'm not a huge fan of the art world because the audience is very limited. So, I'm not using the art world as the main way to disseminate my work." Instead, they are flexible and connect with the public by sharing protocols online and leading performance-based, participatory DIYbio workshops. In addition, transdisciplinary partnerships have the potential to make the practice of bioart more accessible to the public by leveraging relationships with community labs or biohacking spaces. P1 described an initiative to establish artist residencies at a handful of community biology spaces, "and the framework for that grant is how do we get this information out into communities and part of a community participation type thing." This observation connects with the theme about access and is the result of collaboration that raises community needs and values above disciplinary constraints.

Finally, the transdisciplinary fluency that bioart practice brings about enables artists to critique contemporary beliefs and practices driven by scientific and cultural imperialism, such as false or rigid binaries and taxonomies.

For most of the bioartists we interviewed, this begins with questioning the superiority of humans over other living beings and the separation of humans from each other and from other beings into discrete categories. This motivation was expressed explicitly, such as by P6 who said, "I think I do talk about the idea of re-centering our human perspective to see a nonhuman perspective for its own sake." This takes shape in her work: "it was an artwork for the birds, and it's part of the series that I call a cross-species artwork where humans and nonhumans can share in an experience." Biologist collaborators also participate in this aspect of the transdisciplinary endeavor, with artists relating conversations with collaborators about difficulties categorizing organisms and discoveries that counter dominate narratives about taxonomy. Bioartists see challenges and opportunities for re-centering, such as P3, "I feel like the whole scientific institution is built in this way of reductionist thinking, whereas if you look at Lynn Margulis, a feminist scientist, she was looking at everything as in symbiosis with each other." Bioart itself challenges boundaries, creating space for new kinds of expression. To P5, there is a balance to be made between biology and art in the search for effective communication with the public:

> "One thinks about this as art, and someone think[s] about this as not art. And this always will be a confliction. And it's always where, for example, confliction, 'Oh, do you think this is science or art?' That's why there is just really kind of the border which you just need to not really close to science, from my perspective, not just the going so much science. But at the same time, you can have some element, some things from there. So definitely, someone will change their idea."

3.2.2 The Familiarity of Living Media

Participants described living media in a variety of ways that point to a sense of familiarity. Living media carry cultural significance and symbolic meaning as well as information that can be analyzed, manipulated, processed, or perceptualized [18]. The artists we interviewed all spoke of working with living media connected to their community or even from their own body. Living media invoke strong emotions and lead artists and viewers to contemplate bodies, including human bodies, as living media. Finally, artists describe devising ways to highlight self-referential qualities of living media that underline their vitality, interconnection, and agency.

One of the most important qualities of living media for the bioartists we interviewed is the meaning or significance it carries. Living media can embody significant meaning, including embedded symbolic and cultural information about identity, history, and potential. P5 described the use of symbolic meaning in one of her works in which women from her home country contributed crocheted pouches to honor victims of femicide. She weighed the symbolic meaning of flowers compared with unadorned grave markers on a green field:

> "And I just researched all monument, especially from [country of origin]. And they have some standards. They are just one marble and then all the grass. And at the same time, before, I tried to do some flowers. And then, after, when it just come to like 300 [pouches], and I thought that—I mean, it should look like exactly monument. And then I decided to just grow grass."

P3 described informational meaning in living media: "hormones can act as a form of information because they tell you if you had a lot of coffee that day or if you're stressed or if you are on birth control pills. … they tell you so much about that person." DNA is used in most of our participants' practices (P1, P2, P3, P4, P6). Two participants (P3, P4) pointed out the limitations of the common "DNA-as-code" metaphor, as P4 went on to describe, "This whole notion in synthetic biology that 'DNA is the software, the cell is the hardware,' and you can just load whatever code you want into this machine, like you can just put your plasma into the *E. coli* like it's putting a floppy disk in the computer. It doesn't work like that." The reason it does not work like that, according to P4, is the ethical considerations that genetic engineering raises: "Could you engineer a dog to eat grass and make milk? It's like, probably, but cows already do that. So why don't we just work with cows?" These participants acknowledged that DNA contains a lot of powerful information and can be manipulated to dramatic ends. While P4 questioned the ethics, P3 questioned the feasibility, given the unpredictability of living media: "science is all about cutting out elements, creating a very narrow and programmable environment, whereas, in the real world, nothing is ever like that. Everything is constantly mixing and cross-contaminating and living with each other, and it's not this highly controlled and highly characterized environment of a laboratory." Living media can also inform us about the environment. Reflecting on complex structures, P2 described the work of a biologist associate: "she's collecting spiderwebs from different places and in particular south Baltimore and then looking at what's in the spider web that's been collected, from micro-dust and materials. Looking at air quality. Also looking at the body mass of the spider, you can tell how healthy it is and that reflects on how healthy the environment is."

Each of our participants also described working with living media found close to home: in their communities or even in their bodies. Choosing to work with local organisms was sometimes described in terms of convenience, but more often because of special interest and importance in connection with human concerns. P2 described working with local organisms out of a concern for the environment and sustainability of traditional ways of life, shared with biologist collaborators:

> "We know what we're doing here is impacting it in a local way. Larger, global systems are impacted if that is sick. So, if we look at all the dead zones in the Inner Harbor, which are where there's no oxygen or minimal oxygen in the water supply, that impacts all the biodiversity. It goes back to the things that we love, which are good quality food: the striped bass, the oysters, the crabs."

Interaction with living media also has emotional dimensions. The artists we interviewed described feeling joy, love, curiosity, excitement, and even anger in the course of their work with living media. The two most common and most extensively referred to affective experiences described were care and concern for the organisms and their ecosystems, and wonder. Regarding an installation that represented the presence of microorganisms with sound, P2 asked, "can we learn from those sounds, and then can we act on them when we know that the sounds that they're generating is a primal scream for help?" This question invites concern for the organisms in their natural environment. Participants also expressed concern regarding manipulation of living media, such as described by P1: "I think there's concerns about—not so much with bacteria, but maybe with bacteria—when you're exhibiting that as bioart or manipulating it, there's a very clear hierarchical kind of issue of, even what if my bioart piece is dependent on somebody else's metabolic process and I'm manipulating it." At the same time, participants also described fascination and awe. P4 noted an array of emotions, perhaps experienced at different levels of intensity: "I do enjoy the kind of the technical challenges of this work, as well. It's fun. There's a lot of great little riddles to solve. There's all sorts of different sympathies you have to develop in this process as well that just makes you—just expands you as a person." Drawing on symbolic meaning and transdisciplinary appreciation, P1 described learning of the systematic breeding of camellias, connecting to the human aspect of that history with wonder: "Somebody was so interested in these intricacies of form and color and I was just like, 'Oh my God, that's incredible.'" Participants also described audiences experiencing bioart as disgusting, intriguing, exciting, peaceful, and unsettling. "[P]eople are moved. People hugged me," said P6 about the public exhibition of her recent work.

The artists we interviewed observed and acknowledged the agency of living media. P2 described his experience studying specimens from a terrarium project through a microscope, saying, “It’s got its own system that’s in play …. Or being around a very intelligent person. It’s highly intuitive.” P5 framed this as illustrative of the limits of control saying, “And these things, they are also artists. And they are also part of my work. And they are just having their existence by their self. They can die, or they can just still to be alive, but which I cannot control. I control ‘til somewhere.”

Participants described how living media can convey information about itself and its environment through itself. Using artistic techniques to heighten the recursive and performative aspects of living media may be a way for artists to draw attention to the agency they perceive through close, hands-on study over time and the emotions experienced in the course of this work. In a piece by P6, a system in which the vibration of music is based on an organism’s bioluminescent DNA sequence was used to irritate the organisms in a tank of water: “So during the installation, I just stuck this [music] in. [Music plays in the background.] And so this was agitating the water. So literally, they were bioluminescing according to their own DNA.” As the organisms produced light according to the sound of their own light-producing DNA sequence, the shape of the tank was illuminated. P2 brings the human into the interaction: “So, if the viewer came up and looked at the monitor, they would break the—and then the sound changed drastically. So, then you realized, ‘Oh, I’m becoming part of the piece—and that was intentional.” P4 described his work as interactive in a slightly different self-focused way:

> “I would say [pause] some pieces are interactive. I would say most pieces are maybe what I would call performative in some regard, in that they do something, whether that is something that they do to the viewer and the viewers does something back, that sort of interaction. Sometimes they just do a thing to the viewer and the viewer has to deal with it. Yeah. Sometimes they do a thing to something else and just create a different relationship there.”

Profound emotional responses to working with living media and to experiencing bioart point to a familiarity or kinship between humans and living media. This is perhaps best demonstrated by the artists describing human bodies as living media in their work. P3 told us, “it’s kind of funny because I understand what you mean when you phrase your questions with, like, ‘living media’ because I guess you’re thinking about scientists or artists working with organisms. But I actually in my work—I am working with living media, but the living media is people. The hormones affect people.” P2 described the capabilities or affordances of the human body in the same way he describes those of the living organisms he works with:

> “We’ve detached ourselves from one of the most powerful senses. But if you look at the purpose of olfactory, we’re basically talking about a chemical system. In the bio world, that’s essential for survival for organisms, is that ability to smell a prey or smell danger. It’s quite fascinating, and we sort of, this is what we do now for most of our lives, is we hold our nose where we should be actually taking that in and learning from it and [deep breath in] not detach ourselves from that particular sense.”

In terms of their emotional response and acknowledgement of the agency of living media, several participants described viewing the organisms they worked with as individuals. For example, when reflecting on whether a project could be characterized as bioart, P6 described how this work narrowed the distance between the Subject and the Object—a human and a red-tail hawk. In this work, P6 designed a space naturally visible to birds but only artificially made visible to humans and invited the hawk to spend time there together with human viewers. “I would say, the first project that you might be able to call bioart was this—it doesn't actually use the media in the way you're defining it, but it's called—what is it called? [laughter] *Rembrandt in his Studio*, which was a project for the birds. So, it was an artwork for the birds." She then clarifies, "It just doesn't use live [media] except there was a bird, there was a bird." Also highlighting a narrowing distance between Subjectivity and Objectivity, P5 described her work with living media originating from the human body, and said, "as I told you, you are working another living organism. You are also a living organism."

3.2.3 Negotiating Access

We found participants describing ways that access to both biological materials, equipment, and knowledge as well as access to art are critical and must be actively negotiated in one or both of two distinct senses: careful and concentrated wayfinding in unknown territory and seeking compromise between competing interests. Regarding the importance of this work, the artists we spoke with highlighted concerns about concentration of power and protection and advancement of human rights such as equitable distribution of resources, access to education and knowledge, and meaningful participation in art, science, and civil society. They also spoke of the catastrophic consequences of failure to adequately negotiate access. Speaking about the ethics of manipulating living organisms at the molecular level, such as through gene editing, P1 said:

> "You know, I think it's so important to us to look and reflect on the history of these issues and the history of eugenics is always brought up with that and then quickly dismissed as 'we're not, we're not doing that.' … [Eugenics is] not a German history: that's a history that initiated in the United States. And that's a history that we can see playing out very strongly in terms of current issues of racism and the rise of Neo-Nazism."

P4 raised this issue in similar terms, saying, "we can't afford the sort of, what the tech bros have brought us with digital technologies, we can't afford to do that with biotechnologies because the consequences are too high and the reach is too deep on those things." These statements reflect the artists' concerns about decision-making that does not include marginalized or oppressed individuals and communities. This is especially consequential when it comes to biotechnology, which, through genetic engineering, has the potential to forever impact life on earth in ways determined by decision-makers. Participants warned that equitable access to knowledge and education are essential to avoid this future.

The artists spoke about both experiencing and advocating for an approach to biology and art that supports creative and participatory abilities, respects rights to self-determination, and prioritizes the inclusion of underrepresented voices as an important part of negotiating access. Their approach applies to how we think and make decisions about a variety of issues and configurations, including K-12 STEM education, community and public access to resources and knowledge, how we fund art, and how resources are distributed. Describing his experience as a novice learner participating in a distributed DIYbio class organized by Harvard and MIT P4 said, "You'd learn about like, gene drives from the guy who's doing the primary research on gene drives. So, a lot of the things were like, 'Hey, this is what I did for my dissertation. Why don't you do it this week?' Like, 'Oh, okay.'" This illustrates the surprise that even established professionals experience when advanced biology concepts and methods are made accessible. Viewed another way, P6 contrasted her experience designing engaging and participatory bioart installations with the expectations her biologist collaborators at first had of the public, saying, "one thing I can say to the scientists who want to do this K through 12 thing is, 'You give these people agency. The questions come from them. It's not top-down anymore.'" Four of our participants (P1, P2, P3, P5) spoke of reducing barriers to public involvement in art creation as well. Speaking of the impact of his work, P2 reflected, "I have a theory that the more people making art, the healthier we would be."

Half of the artists we interviewed (P1, P3, P5) are involved with negotiating access with international collaborators. Two (P3, P5) described personal experiences with lack of access to laboratory equipment and protocols. Describing her involvement in the Global Community Bio Fellows Program (a "professional development, leadership training, and peer support [program] for emerging leaders" organized annually as part of the Global Community Biosummit by the MIT Community Biology Initiative and MIT Media Lab [29], P1 said of her group:

> "[W]e wanted to initially share artistic protocols. But the first discussion from a number of the people in the Global South was we don't have the equipment nor the reagents to participate in these joint protocols. So, the focus of our group became how to move used lab equipment from the Global North to the Global South within the community bio network that we're trying to create. How do we actually get access to places that can easily do that?"

P5 described being unable to find a "special place" in her home country where artists can work freely in a laboratory, eventually working in a hospital lab through access negotiated with a friend who worked there. P5 also described working to create a place for expression and participation for oppressed women using accessible materials and protocols, saying:

> "And especially for last years, in [country of origin] woman even cannot protest because to making the protest is forbidden. And so, at least, they are feeling better because they are just making these small pouches from their really small town and sending [them] to United States, and someone can see, which to make them like awareness about this femicide all over the world."

Finally, bioartists spoke of the need to "turn something invisible visible" as a means of opening access to engagement. P3, who has formal biology training, described their work as driven by this aspect of access, saying:

> "[I]t's really important to me to create these hormone-hacking protocols because you turn something invisible visible. And I think for participants that I've worked with in workshops, for them to see hormones extracted from their urine is super, super, I don't know—shocking and surprising and kind of like groundbreaking for them."

All of the artists we interviewed described raising awareness and visibility in their work with living media. Describing his work process with marine microorganisms, P2 described the process of negotiating access to information through visibility, "they scrape a sample from there and they do a DNA sequence to see all the organisms that are invisible to the human eye." P6 described an installation in which she used bioluminescent microorganisms to bring visibility to the organisms' presence: "…you pour them in and then as you speak, you say, 'What is the shape of water?' The idea is the dinoflagellates will tell you through light, right?"

4 RAAZ: A TRANSDISCPILINARY EXPLORATION INTO DIY BIOART

We are conducting an ongoing bioart project that began more than two years ago. *Raaz* (Farsi: راز) explores concepts of transformation and survival through the encoding and inserting of a line of poetry from a famous Persian ghazal by the 14th century poet Khajeh Mohammad Hafiz Shirazi into the DNA sequence of living *Saccharomyces cerevisiae* yeast cells. In the following subsections, we will first describe the project's creative concept. We follow with a description of the DIYbio community lab where the project is taking place and the synthetic biology procedures we employed to achieve our creative goals. Finally, we present a reflection on our process with a focus on the transdisciplinarity and interactivity of the project's creative activities.

4.1.1 Artistic Concept

Raaz (Farsi: راز) is a bioart installation that consists of a bottle of transgenic poetry-infused wine. The wine is fermented using *Saccharomyces cerevisiae* yeast cells whose DNA is genetically modified using DIYbio synthetic biology methods to include an encoded 14th century Persian poem by the Sufi poet Khajeh Mohammad Hafiz Shirazi (Farsi: خواجه شمس‌الدین محمد حافظ شیرازی) who used the pen name Hafiz (حافظ) (aka Hafez and Hafiz of Shiraz). The installation explores themes of transformation, the cultural significance of wine in Sufi poetry, and the relationship between biology, poetry, and information.

The poem (Figure 1) is a famous line from a longer *ghazal*, a classic Persian poetic form, and has been translated many times into English and other European languages since the late 18th century. It was first translated into English in 1771 by William Jones, and later into German by Joseph von Hammer-Purgstall in 1812 [57]. The following is a classic translation by William Clark from 1891:

"Never dieth that one, whose heart is alive with love:
On the world's record, is written the everlasting existence of ours." [35]

Western translations of Hafiz's poetry have been controversial due to their links with colonialism and Orientalism [53]. For example, Clark was a colonial officer in India when he translated the above poem. More recently, Omid Safi has criticized a series of best-selling books of poetry by US author Daniel Ladinsky that were incorrectly attributed to Hafiz but written by Ladinsky himself [68].

A more contemporary translation of the poem by the first author follows:

"One whose heart is vitalized by Love never dies:
Our continuity is written on the face of time."

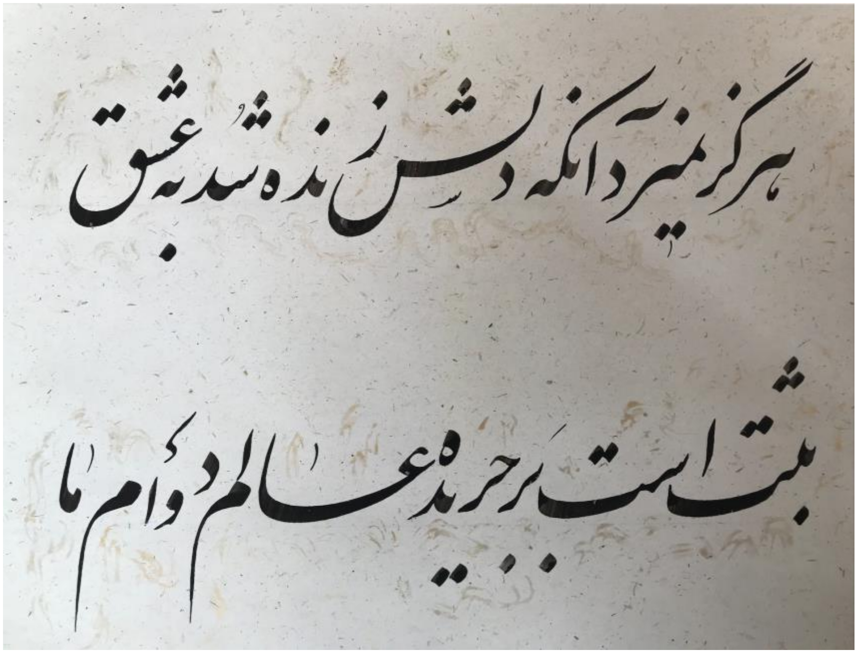

Figure 1. The Farsi poem in Nastaliq calligraphy, a technique developed in the 14th century (owned by first author)

Hafiz was born in in Shiraz (Farsi: شیراز), a desert city in Southern Iran known for its poetry and wine, in 1315 [57]. His name translates to *memorizer* in Arabic and historians have argued that he was given this name because of his remarkable ability for memorizing poetry and verse, and specifically the entire book of Quran, the holy book of Islam. The practice of memorizing sacred texts for spiritual as well as practical purposes is central to Islam and historically crucial for Islam's survival as a faith [62]. Hafiz's poetry collection, known as the *Divan of Hafez,* is one of the most popular poetry books in present-day Iran. The poems are regularly memorized in Iran and recited at significant events such as weddings and new year celebrations.

Wine (Farsi: شراب) and fermentation have a long history as powerful and controversial metaphors in Sufi poetry [67][66]. One common interpretation is for fermentation to stand as a metaphor for spiritual transformation that turns grapes (human potential) into wine (transcendent spirituality). Other interpretations have likened inebriation due to drinking wine to becoming intoxicated by divine love. Another layer of complexity surrounds these metaphors since drinking alcohol and wine is prohibited in Islam (and currently illegal in Iran). Therefore, drinking or making wine also symbolizes forbidden and subversive acts of transcendence that deviate from conservative interpretations of religion. The difficulty of capturing these cultural complexities in translations of Sufi poetry has been noted previously [24][53][70]. In this context, the tension present in fermenting wine or writing mystical poetry as a creative act is reminiscent of the notoriety that sometimes surrounds the work of bioartists who often interrogate prevalent social and cultural norms in working with genetically modified organisms [58]. Incidentally, the Western cultural aspects of wine have recently received some attention in HCI [65].

Raaz means "secret" or "mystery" in Farsi and we use it to refer simultaneously to the invisibility of the poem encoded in the yeast cell's DNA sequence, and the ambiguity of the metaphor of wine, as both a spiritual and a material concept—and as both sacred and taboo. The word also has further significance in Farsi in that if the central letter, ‘a’ (Farsi: ا), is dropped the word becomes *Raz* (Farsi: رز) which is another word for wine. Therefore, in the Farsi interpretation, the word “wine” is hidden in the word “secret.”

The current project references a canonical bioart piece by Brazilian poet and bioartist Eduardo Kac. In *Genesis* (1999), Kac used synthetic biology processes to encode an English translation of a line from the Bible into the DNA sequence of living bacteria [41][42]. He then displayed the bacteria in an interactive installation that could be accessed remotely over the Internet or experienced in person. Kac has described the project as an exploration of the “manifold relations between biology, belief systems, information technology, dialogical interaction, ethics and the Internet” [42]. In *Raaz*, we continue this exploration by moving beyond Western-centric cultural orientations and paying homage to the resilient spirit of Persian mystic poets who used the power of metaphors and linguistic transmutations to capture vivid experiences of personal and spiritual transformation and ensure that their poetry survived oppressive orthodox religious and political doctrines and agendas.

Raaz differs from the earlier project in that it engages with an additional ethical dimension. As described above, wine (and the process of producing it) is taboo in Islamic traditions, which is precisely why it is used in Sufi poetry as a poetic metaphor for a dangerous but necessary spiritual transformation. By turning the key metaphorical concept of wine from the Sufi tradition into material reality, *Raaz*’s engagement with the process of winemaking parallels the ethically ambiguous practice of genetically modifying living organisms [75]. *Raaz* further contributes to diversifying the bioart field by bringing in a non-Western perspective to a space dominated by Western artistic and scientific perspectives [21]. In addition to these distinctions, *Raaz* differs from *Genesis* with respect to the living media and biological processes employed, thereby extending the scope of materials used in the HCI-bioart space. In another similar project, *The Last Supper* (2018), artist Karolina Zyniewicz genetically modified yeast to include a gene from the artist’s genome which was then used to ferment beer and make bread that were ritually consumed by the artist and her colleagues [78]. Despite similarities in drawing on religious symbolism and genetically modified food, this project differs from *Raaz* in that it is situated in the Christian tradition and uses different materials (i.e., beer and bread).

4.1.2 Team Composition and DIYbio Context

Our transdisciplinary team consists of three HCI researchers (one with expertise in the design and evaluation of LMIs), a bioartist, and a synthetic biology researcher and educator who is also the director of the community lab in which the research took place.

The synthetic biology procedures necessary for the project took place at a local DIYbio lab. The Baltimore Underground Science Space (BUGSS) is a BSL-1 facility that offers affordable courses, seminars, workshops and biology lab space to members of the public. BUGSS is located in the city of Baltimore, Maryland and serves more than 450 members and visitors each year. Courses at BUGSS offer hands-on immersion in biotechnology and past courses have allowed participants to analyze the content of probiotic pills, test their own DNA for genetic variants related to stress resilience, and test foods for the presence genetic modification. Seminars often focus on the intersection of science and society, including the efficacy of commercial cannabidiol products, changes to the Chesapeake Bay environment, and the effects of racial disparities in health care. Workshops at BUGSS are distinct for their interdisciplinary nature, frequently incorporating bioinformatics or bioart themes such as bioluminescence. Finally, BUGSS like most DIY-biology spaces, facilitates independent and community projects; examples include Barcoding the Harbor, which uses DNA analysis to catalog all organisms living in Baltimore’s harbor, Open Source Gendercodes, which engineers plant cells to produce steroid hormones that could be used for gender transition, and Open Insulin, which is developing infrastructure for community-based manufacturing of insulin for diabetics.

Members of our team are all connected to BUGSS in different capacities. Two of us are based at university that is located 15 miles from BUGSS and are members at BUGSS and regularly participate in learning and research programs taking place there. Another team member is a bioartist and has worked at BUGSS as a lab assistant and course facilitator. Finally, another member of our team is the lab's executive director, member of the Board of Directors, and has designed and conducted multiple learning and community outreach programs there. We all met through pursuing common interests in biology, art and activism and through participating or organizing events in the community lab.

4.1.3 Description of Synthetic Biology Procedures

The steps needed to move from the original poem to the fermenting wine can be broken down into four stages: (1) converting the poem into a viable DNA sequence, (2) having the DNA sequence synthesized and inserting it into a plasmid (a circular DNA capable of propagating the inserted DNA in cells), (3) transforming living yeast cells using the plasmid and verifying that their DNA carries the correct code, and (4) growing the transgenic yeast and using it to ferment grape juice into wine. We next describe these steps in detail.

4.1.3.1 Translating the Poem into DNA Sequence

In a process similar to Kac's in *Genesis* [40], we first translated the Persian poem into Morse code, a binary code that maps each letter of the alphabet to a sequence of dots and dashes. Morse code was developed by Samuel Morse in the 1830's as a method to translate natural language writing to signals that could be transmitted using electrical pulses and silences between them using early telegraph systems [26]. While the Morse code encoding was originally designed for translating the English alphabet, it is widely used with other scripts, including the Persian (or Farsi) alphabet of the original Hafiz poem. We used the common Morse encoding for the Persian alphabet to translate the poem into a series of Morse dots and dashes (Figure 2). Morse code was one of several options for encoding the poem into a binary code that we chose to reference the earlier work by Kac.

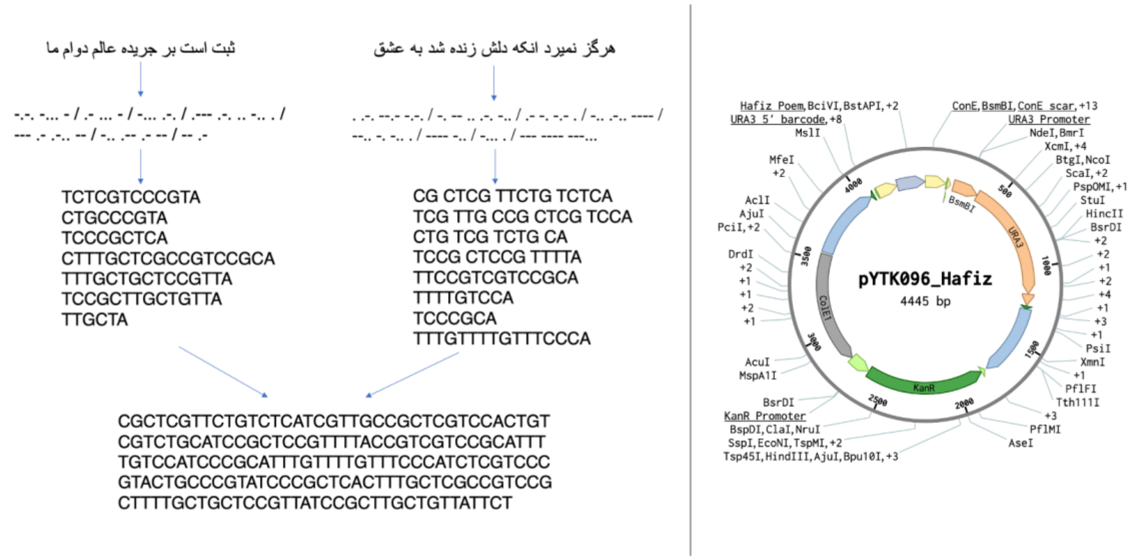

Figure 2: Translating the Persian poem into a DNA sequence (Left). A visualization of the DNA sequence of the plasmid with Hafiz's poem embedded (Right). The circle represents the DNA sequence with numbers representing the nucleotide position. The position at which the Hafiz poem is integrated is depicted. Colored arrows depict functional elements of the plasmid, including the *URA3* and the kanamycin resistance genes (KanR).

Next, we encoded the Morse code sequence into a sequence of letters representing the four nucleotides that make up DNA sequences. For this encoding, we referenced and utilized Kac's approach in the *Genesis* project by replacing dots by the genetic base Cytosine (C), dashes with Thymine (T), spaces between letters with Guanine (G), and word spaces with Adenine (A). This process resulted in a linear sequence consisting of the four nucleotide letters, which through their order encode the information of the poem (Figure 2). While this step concluded the conversion of the poem into a DNA sequence that can be synthesized as a physical molecule, as we will describe in more detail in the next subsection, additional information in the form of DNA nucleotides had to be added to the beginning and end of the sequence to make it viable for integration into a plasmid DNA that would enable its maintenance in living yeast cells in subsequent steps.

4.1.3.2 Cloning the DNA into a Plasmid, Transforming Yeast Cells, and Fermenting Transgenic Wine

After encoding the poem into a DNA sequence, we added additional nucleotides that would allow an enzyme (the *Bsa*I restriction enzyme) to recognize and cut the DNA so that it could be joined to the complementary plasmid DNA, a process called molecular cloning. We added DNA that included the *Bsa*I recognition site as well as an additional 4 nucleotides to facilitate binding of the *Bsa*I enzyme to the DNA. We made these changes so that it would be possible to integrate the DNA segment into a plasmid backbone, pYTK096, that was cut with the same enzyme. Plasmid pYTK096 is part of a plasmid system called MoClo YTK (Modular Cloning Yeast Tool Kit) that we chose because it contains *URA3* homologous ends that can be used for integration into the yeast chromosome through homologous recombination as well as a functional *URA3* gene to serve as the selection marker [50]. *URA3* is a gene on chromosome *V* in yeast that is often used in research as a selection marker on plasmids. Having a selection marker is important because it allows for the selection and growth of only those yeast cells that successfully maintain the customized DNA sequence.

Once the design of the DNA sequence was completed, we sent it to a supplier of custom nucleic acids (Integrated DNA Technologies - IDT) to be chemically synthesized. Once we received the DNA molecules through mail, we performed a Golden Gate reaction to join together the custom DNA and the pYTK096 plasmid backbone. In Golden Gate assembly, an equal number of custom DNA and plasmid DNA molecules (20 femtomoles each) are combined with the enzyme *Bsa*I to cut each DNA sequence and with the enzyme T7 DNA ligase to join the cut fragments together [27], [50]. While the DNA will eventually be integrated into yeast cells, the steps of selecting the plasmid with the newly inserted DNA is first performed in bacteria where the process is more efficient. The product of the reaction was then used to transform bacterial strain *E. coli* DH5α. Some of the bacteria pick up the plasmid DNA into which the custom sequence has been inserted, and we can amplify the synthesized DNA by growing the bacteria in the LB media liquid culture with kanamycin as the selection agent that ensures that only bacterial cells that have picked up plasmid DNA can survive. This process resulted in bacterial cells that could multiply, resulting in numerous living cells containing our desired genetic segment. With the addition of 15% glycerol, bacterial cells are also amenable to freezing at -80˚C, allowing us to "bank" our DNA in the bacterial cells for long-term storage.

Following the amplification, we conducted a miniprep to extract the plasmid containing the DNA sequence from bacteria cells using Promega's Wizard SV miniprep kit. To check that the ligation of the DNA into the plasmid took place correctly and that the resulting plasmids contain the DNA sequence encoding the poem, we performed another enzyme digest that used the *BsmBI* enzyme to cut a sample of the extracted plasmid into 2 fragments. We then verified that one fragment is 504 base pairs long (the expected size if it contains the Hafiz sequence), and the other 3,941 base pairs long by running the enzyme digest on an electrophoresis gel which separates DNA fragments by size.

We next linearized the plasmid so that the DNA segment including the poem could be integrated into the genome of yeast cells. This process involved adding *NotI* restriction enzymes to the plasmid to cut the linear gene fragment back out of the circular plasmid structure. Finally, we transformed yeast cells with the linearized fragment and selected for yeast colonies that successfully integrated the Hafiz gene into their genome through the process of homologous recombination. Sequences framing the Hafiz poem and *URA3* gene are homologous, and this homology guides the linearized gene fragment to integrate into the yeast genome at the site of the *URA3* gene through the inherent cellular process of homologous recombination. We used a strain of yeast (BY4741) with an interrupted *URA3* gene rendering it unable to produce uracil. We chose this strain because it will not survive if grown on uracil-deficient nutrient media unless it has integrated the linear DNA fragment that in addition to the poem contains a functional *URA3* gene. We re-plated any surviving yeast onto new plates lacking uracil to eliminate any background cells that did not pick up the DNA. At the end of this process, we had a colony of yeast cells with integrated DNA sequence containing Hafiz's poem.

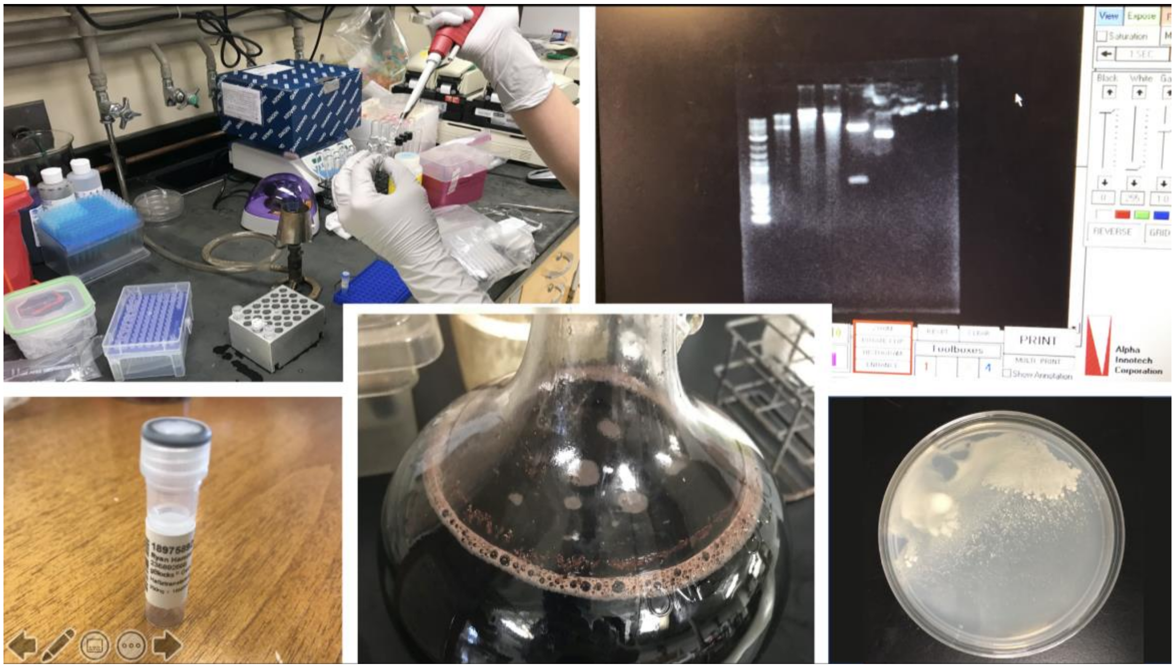

Figure 3: Steps in creating *Raaz* (Clockwise from Bottom Left): the synthesized DNA molecule; integrating DNA segment into plasmid backbone; verifying that the Hafiz sequence is integrated into plasmid by running an enzyme digest on electrophoresis gel; the resulting yeast cells containing the Hafiz poem's DNA sequence in a petri dish; the grape juice fermenting into wine using the genetically-modified yeast.

Once the transgenic yeast was created, we grew it over several days in rich media (YPD; yeast extract-peptone-dextrose) to ensure we had enough cells to ferment a gallon of wine. We calculated the necessary amount of laboratory gown yeast following Harsch et al. who used 2.5×10^6 yeast cells per 150 mL of grape juice [36]. We then harvested the cells by centrifugation, washed them twice with water to remove residual media, and combined the yeast with red grape juice in a sterilized container which we incubated at room temperature. After a period of 2 weeks, we collected and bottled the transgenic wine.

4.1.4 Reflections on Creative Process

Conducting the project provided ample opportunities for reflection, discussion and collaboration within our team. For the purposes of this paper, we focus on three areas of reflection most relevant to the HCI community: opportunities for transdisciplinary collaboration, navigating practical and aesthetic challenges, and experiencing interaction at a molecular level.

Raaz draws on techniques and knowledge from biology, art, and HCI applied toward the transdisciplinary goal of raising critical awareness of the potential of synthetic biology, accessibility of knowledge and materials, and poetic and practical opportunities to challenge dominant epistemologies informing technological development. This transdisciplinarity provided rich opportunities for learning and collaboration among our diverse team, as we were not concerned with perceived hierarchies in values, methods and reasoning (VMR) [9] but rather with the creative vision. The first author, who prior to the project had no experience working in a wet lab, conceptualized the artistic vision for the project. With help and hands-on guidance from two other team members with extensive experience and knowledge in biology, the team figured out the implementation details, including the steps described in section 4.1.4. The first author's relationship with synthetic biology methods shifted through the course of the project from a passive observer of lab procedures to an active participant who completed the needed synthetic biology procedures with guidance and advice from the more experienced team members. The process led to considerable learning of both hands-on lab techniques and theoretical and scientific knowledge behind the required procedures.

Completing the project also involved navigating a number of practical and aesthetic challenges: How can we visualize, sonify, or otherwise represent information by working with living organisms at the molecular level? What biosafety and bioethics standard should be followed when working with specific living organisms? How do we determine if particular synthetic biology procedures were successful or not? Answering these questions required specialized knowledge and experience and we found shared knowledge both in our team and in the DIYbio lab community instrumental to conducting the project. For example, with respect to determining whether the wine can be safely consumed, we consulted with and deferred to the DIYbio lab's advisory board, which consists of experienced biologists, educators and researchers. Furthermore, because a key value in the DIYbio community is transparency, some of the details of the project were shared with the lab's executive director at the onset to ensure it could be conducted safely in the community lab. The heightened attention to ethics in DIYbio can encourage HCI collaborators to carefully consider ethical dimensions of technological design and development more broadly. While bioethics in bioart are important, the discussion of ethics raised by bioart extends beyond these toward the consideration of what bioart can *do*, for example, to an audience [75].

Finally, the project offered a possibility to interact with living organisms on a molecular level. The first author has extensive experience in physical computing design and prototyping and found notable similarities and differences between these activities and conducting synthetic biology procedures in the community lab. Specifically, the tangibility of lab equipment such as pipets, centrifuge machines, and electrophoresis gel equipment resembled the physicality of 3D printers, microcontrollers and other electronic components. However, much more precision was required to work effectively with living yeast cells and plasmid structures and particular attention needed to be paid to the temporal characteristics of these materials. Additionally, while the conceptual design and background research for the project could be conducted anywhere, the biological procedures needed to take place in the DIYbio lab both for practical reasons, for example having access to precision equipment and continued guidance from other lab members, and to ensure biosafety, for example ensuring bioactive materials are disposed of correctly and genetically modified organisms are not released into the environment.

5 DISCUSSION

5.1 The Transdisciplinarity of Bioart

A central thread that connected themes in our interviews and our hands-on bioart project is *transdisciplinarity*, an approach well-discussed previously in HCI and beyond, but challenging to implement within disciplinary structures, even interdisciplinary ones. At the core of transdisciplinarity is the notion of a non-duality of subject and object and their unity through a "hidden third" [63]. This element was present when bioartists discussed the familiarity of living media, exemplified through analysis of the body as living media, and also when they discussed the shared quality of vitality that exists between us and other nonhuman organisms [58]. Our findings and hands-on experience are also similar to two other aspects of transdisciplinary: working beyond disciplines and orientation toward values, and social responsivity [12]. The artists we interviewed described a variety of experiences overcoming barriers to engaging in bioart, including finding access to space, materials, and training. They described learning from and about living organisms and their ecologies by close observation and manipulation. Finally, they described collaborating with biologists, technologists, other artists, audiences, and the public, and the hope that their work might serve to expand access to science, technology, and art for empowering and participatory futures.

While interdisciplinary learning and collaboration is integral to bioart, we see this type of work as fundamentally transdisciplinary due to an observed tendency for both artists and their biologist collaborators to assume a fluency in the knowledge and ways of thinking of the other, resisting hierarchical perceptions of VMR, and thereby generating a way of working that transcends disciplinary boundaries. Participants described gardening, crocheting, bioprinting, videography, audio engineering, and using specialized biology lab equipment with a maker or hacker sensibility similar to that which has also impacted HCI (e.g., [5][51]). Nicolescu and Ertas describe the need for transdisciplinary work in engineering, writing that, "While multi-disciplinary and inter-disciplinary approaches have certainly produced some interesting developments, the focus has primarily been the artifact as a complex system not the artifact as *part* of a complex adaptive system" ([64] p. viii, emphasis in original). Within HCI, this approach has been endorsed by Blevis et al., who explore transdisciplinary design as a fourth design paradigm for HCI [11]. Transdisciplinary research and design are oriented toward values beyond building disciplinary domains of expertise: they are socially relevant. Our analysis of interviews with bioartists and our hands-on transdisciplinary collaboration further supports and underlines the need for transdisciplinarity in HCI and design education [11], and extends the scope of transdisciplinary modes of work to include research and practice that takes place in new contexts such as community labs, informal DIYbio spaces, and other sites of social engagement. Our work shows that bioart offers exciting modes of inquiry for HCI that are inherently transdisciplinary and can be characterized as "art research" [23], provide a space of inquiry rather than problem-solving or "problem-setting" [10], and engage with biological media that may exhibit interactive qualities, opening up new ways of understanding interaction with nonhuman entities.

5.2 (Re)encountering Living Organisms

Another thread relevant to HCI that runs through this research relates to the materiality and significance of living organisms and how these can be creatively explored for artistic and activist aims. We found that interacting with and manipulating living organisms at a molecular level can paradoxically shed light on much larger structures of access and power that surround our relationship with living organisms and the environments they live in. While previous work in HCI that has studied the incorporation of living organisms in interactive systems has exploited affective aspects of interacting with living organisms—for example by motivating children to complete therapeutic activities as a way to care for living mushroom colonies [34] or encouraging recycling behavior by using a living plant as indicator of collective participation [38]—the majority of such efforts have focused on the capacity of humans to relate to non-living organisms in the here-and-now as a way to elicit a design aim rather than using the experience of interacting and experiencing living organisms as a tool for social and ethical exploration [56]. This focus on form and function is also present in the related field of biodesign [60][72]. While there is a vibrant body of HCI research that shares bioart's concern for environmental sustainability [8], [25] as well as questions technology equity and access through postcolonial and feminist interpretations [6][39], our findings point to an underexplored opportunity for the HCI community to learn from and be inspired by bioartists' epistemological positionality to complement its value-sensitive designedly investigations. such that it may complement similar and parallel explorations informed by design. Furthermore, bioartists' forays into "turning the invisible visible" contrasts with visions of making technological processes disappear into the background [74], and may provide fresh and complementary tools for inquiring into a future where through the prevalence of embedded ubiquitous technologies, "HCI may become invisible through omnipresence" [32].

Bioartists' attitudes toward living organisms seem to be profoundly impacted by practice: bioartist participants often used living organisms found close to home, or even from their own bodies, amplifying the cultural and personal significance of specific media and connecting to profound human experiences, such as unpredictability, vulnerability, and highly-evolved intelligence, with implications for designers working with human and nonhuman living media. Many artists identified agency as a quality of the living organisms, describing how "sometimes [the living organisms] just do a thing to the viewer and the viewer has to deal with it" and "sometimes [the living organisms] do a thing to something else and just create a different relationship there." Sayes describes the issue as one of methodology rather than theory, with Latour's view of nonhumans as mediators that modify relations between human actors as an incomplete but useful starting point that aids in understanding "the complexity of the associations we form with others and with nonhumans" [69] (p. 145). This acknowledgement of agency underlines a deep attention to affect and power in relation to the living organisms. Affect and power have been described as key determinants of relations between individuals [16]; thus, relating with living organisms at this level signals that bioartists may meet them as individuals, opening the possibility for an identity relationship where human bodies are also re-situated and remembered as living media. Seen in this light, it becomes clear why the bioartists we interviewed are motivated to recreate this relationship in their audience to raise awareness and address various social, political and ethical issues among broad and diverse communities and thereby increase access to knowledge and participation. Understanding this motivation and how it is navigated through art practice can inform the HCI community as it becomes increasingly involved in tackling multifaceted sociopolitical, environmental, and ethical issues.

6 CONCLUSION

Bioart provides an opportunity for transdisciplinary explorations involving diverse voices. Interested participants negotiate access to knowledge, training, space, and material and become immersed in observation and manipulation of living organisms, captivated by the familiar qualities of living media. This results in work that extends beyond disciplinary boundaries to engage audiences in social and political issues. Analyzing interviews with 6 expert artists about their work with living organisms and biologically derived material, we described how bioartists generate transdisciplinary fluency, utilize the familiarity of living media, and negotiate access to resources and knowledge. We also detailed a first-hand account of a collaborative bioart project, including the artistic concept and the scientific protocol, in order to demonstrate the possible contributions of transdisciplinary bioart explorations to HCI and to relate our experience to the themes. These perspectives contribute to our understanding of transdisciplinary HCI research and the qualities of interaction with living media and DNA.

The ecological and social challenges we face today are unprecedented and the need for a mode of work that prioritizes justice and sustainability is arguably more urgent than ever (e.g., [45]). Computing and HCI researchers develop devices, systems, and interaction techniques that will shape the future. Transdisciplinary work, either directly with or in collaboration with bioart, brings this awareness to the fore, informing the ethics and aesthetics of HCI design. In the future, we plan to explore long-term transdisciplinary collaborations with bioartists to investigate the interactive aspects of bioart and its impact on practitioners and audiences. Furthermore, we plan to facilitate conversations as well as hands-on activities for bioartists and HCI researchers and practitioners to participate in together so that we can further investigate intersections and synergies between these fields.

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