

At the seams: DIYbio and opportunities for HCI

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ABSTRACT

DIYbio (Do It Yourself Biology) aims to ‘open source’, tinker and experiment with biology outside of professional settings. In this paper, we present the origins, practices, and challenges of DIYbio initiatives around the world. Our findings depict DIYbio as operating across intersections (*seams*) between a range of stakeholders, materials and concerns. To map out the role of Human Computer Interaction (HCI) across these *seams*, we present design exercises (functional prototypes) that explore three areas for future work: *internal collaboration tools* within the DIYbio and professional community; mechanisms for *external communication* with stakeholders from the general public; and *bio-electronic assemblies* of organic and digital materials. In doing so, we hope to critically re-envision the role of HCI at the emerging intersection of biology, computation and DIY.

Author Keywords

DIYbio, synthetic biology, publics, hybrid materials, DIY

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H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Biology, the study of *living organisms*, has a long history of shaping and being shaped by technology. From early advancements in microscopy, to the more recent sequencing of the human genome, biologists are becoming increasingly reliant on digital tools that support routine work practices. Moreover, the power of modern computational platforms enables the modeling of complex biological systems *in silico*, often replacing aspects of wet-lab experimentation altogether [5]. Also, in some startling cases, the treatment of biological elements as engineered building blocks has led to new biological organisms being synthesized. For instance, 2010 saw the implementation of the first cell controlled by a synthetic genome [17].

Recently, *DIYbio* (Do It Yourself Biology) has emerged as a growing community of professionals and non-experts who pursue biology outside of professional settings. Adopting the language of computation and the practices of other DIY movements, ‘garage biology’ focuses on open-sourcing, hacking and tinkering with biology. The DIYbio.org forum lies at the core of this community with the aim of “making biology an accessible pursuit for

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Figure 1. Swab sample collected by DIYbio Manchester, image source <http://diybio.madlab.org.uk/> (top left); algae biofuel project at London Hackspace (top right); sterilization with pressure cooker at Bosslab, image source <http://bosslab.org/> (bottom left); our speculative prototypes exploring opportunities for HCI at the *seams* (bottom right).

citizen scientists, amateur biologists, and do-it-yourself biological engineers who value openness and safety” [10]. DIYbio projects worldwide cover a spectrum of art, science and engineering, including DNA extraction, embedding bacteria in textiles [14], mapping genetic traits, developing biosensors, or creating lab equipment with off-the-shelf parts, to name a few.

Alongside these developments, biology (professional and DIY) is being discussed as one of the most promising areas of our time [2, 6]. It has been speculated to answer some of our greatest challenges—the global food and water crisis, bio-fuels, medicine, *etc.* At the same time, concerns are regularly voiced about the safety and ethics of biology, especially in the hands of non-experts [28, 41]. Whatever the positions held, the convergence of biology, computation and DIY introduces a host of opportunities and concerns for Human Computer Interaction (HCI). These range from applying more traditional HCI strategies to collecting and sharing biological data [*e.g.*, 42], to the less explored design space around the treatment of living systems as computational machines and the ethics of engineering biology. At the very least, the emerging intersections across biology and computation reignite longstanding debates on the nature of machines and humans’ interactions with them [43, 48].

With this backdrop, our reasons for focusing on DIYbio are twofold. First, DIY initiatives have a trajectory of inspiring and co-evolving with various aspects HCI research [4, 23, 46, *etc.*], including prior innovations in

low-cost electronics [e.g., 5] and citizen science platforms as well as questions of sustainability and reuse [25]. In this paper, we propose to re-envision HCI's role involvement with the DIYBio movement. DIYbio's appropriation of biological components outside traditional laboratories, the resulting hybrid assemblies of living and digital materials and the emerging public discourse around these presents many unexplored design opportunities and challenges.

Second, as a grassroots movement, DIYbio also resonates with an emerging body of research in political computing [e.g., 12]. In particular, HCI has focused on supporting and sustaining *publics*, groups of people that come together to address shared concerns, through design principles, workshops and field deployments [9, 26]. By operating at the fringes of formal biological methods and hacker practices, DIYbio offers a unique point of comparison. For instance, unlike Dewey's publics [8], which emerge from citizens initially *outside* and unaware of their problems, DIYbio operates *within* the science and issues that concern it. That is, DIYbio publics do not exist as groups objecting on the sidelines, but *in-situ* [31], creating, legitimizing and validating their own science practice.

Research objectives

This paper contributes to HCI across two areas. First, we present a qualitative field study of DIYbio practitioners, a previously unexplored community for HCI. Drawing on literature that leverages qualitative fieldwork to understand community values [29, 39, *etc.*] we present a summary of DIYbio origins, practices and motivations. Second, we identify design opportunities from user data and develop three working prototypes as starting points for future research '*at the seams*'. Grounded in the *seamful* computing framework of Chalmers, *et. al* [7], our tangible artifacts operate across three intersections: i) DIYbio and professional biology; ii) DIYbio and the general public; and iii) hybrid assemblies of living organisms and digital technologies. Our prototypes serve to suggest implications for interactive systems at the seams of biology, computation and public engagement.

METHODS

Our research involved several strands of investigation. We began by surveying the origins of the DIYbio movement—as detailed in Wohlsen [49], Carlson [6], Ledford [28] and others—and by reviewing numerous DIYbio community blogs and mailing lists [1, 10, 33]. As another entry point, we organized a workshop with professional and DIY biologists near London, UK. The workshop included presentations, discussions, and structured brainstorming. Themes derived from these were used to conduct follow-up site visits to three professional biology labs in the UK and two DIYbio communities in London and Manchester, each lasting 2-3 hours. In addition, we conducted phone interviews (1-2 hours each) with founders of five major DIYbio groups internationally. In total, we surveyed seven DIYbio initiatives in four countries:

- *Genspace*, New York, USA. genspace.org
- *BiologiGaragen*, Denmark. biologigaragen.org
- *Bosslab*, Boston, USA. bosslab.org
- *Manchester DIYbio*, UK. diybio.madlab.org.uk
- *Indie Biotech*, Dublin, Ireland. indiebiotech.com
- *London Hackspace*, UK. london.hackspace.org.uk
- *BioCurious*, Sunnyvale, CA biocurious.org

We also interviewed a bioartist in the UK, and a biologist at the UN Office for Disarmament Affairs in Geneva, who works on ensuring safe (non-hostile) use of biology. Interviews were recorded, transcribed and coded to themes.

Limitations. Our findings are based on discussions with our participants, and are thus susceptible to self-selection bias. In particular, the people who agreed to speak with us tend to collaborate with academic researchers, and our findings might not be generalizable to other types of practitioners, for instance 'outlaw biologists' [24] working independently. We also note that our phone interviews do not provide insights into the details of routine DIYbio work. Rather, we present participants' reflections on this emerging space, and further research might focus on understanding *in-situ* work practices. We continue by detailing findings across three areas: i) origins and motivations; ii) materials; and iii) public engagement.

DIYBIO ORIGINS AND MOTIVATIONS

Scientific inquiry is often furthered by chance inventions ('hacks') and breakthroughs, such as, for instance, the accidental discovery of penicillin or the adoption of a jam ingredient, agar, as a growth medium. As noted throughout DIYbio literature and mentioned by many of our participants, these examples along with a host of artistic and socio-political influences serve as an inspiration for DIYbio. However, of particular importance has been the development of a novel research area: synthetic biology.

Synthetic biology and iGem

An emerging field itself, *synthetic biology* explores "the design and construction of new biological parts, devices, and systems" and "the re-design of existing, natural biological systems for useful purposes" [45]. Alongside this articulation of biology, the field also introduced initiatives that unsettle the status quo in biological and, more broadly, scientific modes of inquiry. For instance, it has been remarkably open to collaborations with designers and social scientists, as well as engineers. This openness is also reflected in its public sharing of information through forums such as OpenWetWare [35]. Countering the trend of keeping research proprietary, OpenWetWare readily states its aim "to promote the sharing of information, know-how, and wisdom among researchers and groups".

Similarly, the annual International Genetically Engineered Machine competition (iGEM) [21] presents a radical shift for the modes of knowledge dissemination in traditional science research. Instead of adhering to longwinded processes and formal requirements demanded by scientific publications, iGem teams work in short timeframes and

creatively experiment with a *Registry of Standard Biological Parts* [38] to design new biological systems and, as they refer to them, ‘devices’.

Framed in these terms, synthetic biology is presented as a field that just might be dynamic and innovative enough to harness the engineering potential of biology and in doing so, address some of our most pressing challenges [6]. Undoubtedly, this rhetoric has been an important trigger for the DIYbio movement. A famous early DIYbio example is Katherine Aull’s homemade test for hemochromatosis—a genetic blood disorder resulting in over-absorption of iron in the body. Aull was able to accurately test herself for this disease [22] in a lab she built in her home closet using equipment from e-bay. DIYbio is thus inspired by research and discovery, but as we present below, less emphasis is given to strictly reproducing results and more to enabling open access to the scientific experimentation and the tinkering itself.

From synthetic biology to hacking and biohacking

By associating itself with an openness and, in particular, with open-source [e.g., 13], synthetic biology at once identified biology as a resource for tinkering—or ‘bio-hacking’—and a platform open to everyone. Hence it is not surprising that DIYbio cultivated a close association with hacker cultures and practices. For instance, CodeCon, traditionally a computer hacking conference, featured Meredith L. Patterson’s talk on DNA purification techniques using household items in 2005 [36], and dedicated one third of its program to a biohacking track in 2009. Many of today’s DIYbio groups including Bosslab, DIYbio Manchester and BiologiGaragen are hosted within existing hackspaces, while others (e.g., BioCurious, Genspace) regularly collaborate with local DIY groups.

Similarly, DIYbio’s motivations appeared to emerge from the conjoining of synthetic biology and hacker/open-source movements. As the co-founder of Genspace explains, the ability to access science outside of traditional institutions is in itself a primary motivation for DIYbio: “*So our main goal is to make synthetic biology happen... I want to view it more as making science itself more accessible.*” In addition, what appeared to catch the imagination of DIYbio founders and the fledgling community, were flexible ideas of experimentation and creativity. In the words of Bosslab and DIYbio.org co-founder, “*You should be able to build things that are cool. And that’s the reason to do stuff in and of itself.*”

To varying degrees, all of our interviewees emphasize creative tinkering and the fun of “*playing with science*”, but this hands-on experimentation is closely coupled with wanting to learn. For our participants, DIYbio serves as a resource for understanding information that has been traditionally limited to academic literature or unavailable altogether due to proprietary law and other factors. Thus, equally important though less emphasized, is DIYbio’s aspiration to disrupt conventional patterns of knowledge

transfer in academic research. These motivations—open access, creative tinkering, learning, and unsettling traditional modes of science making—echo values embedded in previously studied DIY and hacker groups [e.g., 46]. Unlike other DIY groups however, the resulting DIYbio community remains embedded in and dependent on the discourse between professionals and non-experts.

DIYbio communities of professionals and non-experts

What evolved is a loosely coordinated community of distributed DIYbio labs, engaging with biology through hacking and tinkering outside of traditional institutions. The DIYbio.org organization [10], founded by Mackenzie Cowell and Jason Bobe in 2008, serves as a meeting point for practitioners around the world. The public mailing list boasts over 1900 members—from professional scientists and biotech entrepreneurs, to artists, founders of DIYbio labs, and hobbyists with no biology background.

So DIYbio is one source of like hey, I want to do blank what do I do. There’s a lot of people on there who are PhD students or who are scientists or have done this, a lot who will chime in and say oh yea do this... so you can just like interact with a spectrum of practitioners.

Above, DIYbio.org’s co-founder, who himself holds a biology degree, emphasizes the role of expertise in sharing DIYbio knowledge. Indeed, to varying degrees, all DIYbio groups we surveyed serve as platforms for collaboration between professionals and non-experts. We now briefly summarize the workings of three initiatives—Genspace (USA), Indie Biotech (Ireland) and Manchester (UK)—as a diverse cross-section exemplifying these relationships.

Genspace. Genspace [15]—today’s most active DIYbio lab—was started by two undergraduate students, a science journalist and an employee at a biotech company as a meet-up in New York City in 2009. The group was hosted at NYCResistor, an established non-bio hackerspace. They grew to include eleven active members and eventually established a BSL1-certified lab within a collective of artists and engineers in Brooklyn. While Genspace models their community on the hacker space design patterns¹, their work is informed by feedback from professionals:

From early on we found out that we couldn’t really build and run... a biotech lab whether it’s DIY bio or community or synthetic biology or whatever... We really needed to get in touch with people who are actually doing biological research could help us out, give us advice.

Consequently, Genspace is affiliated with an advisory board of scientists who assess safety procedures and back the group’s biosafety certification. By aligning themselves with professionals, Genspace also receives equipment from laboratories that move, downsize or upgrade. Today, Genspace is self-funded and open 24-7, hosting a variety of projects that focus on topics such as biological lasers,

¹ http://hackerspaces.org/wiki/Design_Patterns

temperature biosensors and microscopes from webcams, as well as running many public workshops and classes.

Indie Biotech. Indie Biotech [20] is a startup company in Ireland, aimed at creating affordable equipment and methods for practitioners working outside of academically funded labs. The founder, Cathal Garvey holds a genetics degree and works in a lab he built in his parents' house. Garvey emphasizes the importance of science “*in the hands of individuals, not corporations and governments*”, and is thus the first individual to acquire an EPA certification for working with genetically engineered organisms in Ireland. His most recent project is a new plasmid for *Bacillus subtilis*—a laboratory-safe strain of bacteria—to make DIYbio projects safer, more reliable and antibiotic-free. Earlier, he also developed the *dremelfuge*, a 3D printed accessory that can be attached to a regular dremel and serve as a centrifuge. Like the rest of Indie Biotech's products, the *dremelfuge* costs a fraction of the price of its professional counterpart.

Manchester DIYbio. This UK community formed in March 2011 as a collaboration between Manchester Metropolitan University and Madlab—an independent hackspace. Professors partnered with Madlab as part of the university's Nano-Info-Bio program², which supports interdisciplinary research and public engagement with science. The resulting DIYbio initiative is funded by the WellcomeTrust³, UK's largest independent charity for medical research. The group's monthly meetings tend to be led by the core organizers (mostly academics) but involve hands-on participation from all attendees (usually 20-30 people). For instance, during the first project, *Swabfest*, participants collected swab samples from local bus stops. These were cultured by the organizers at Madlab, and participants returned to conduct colony counts later. While initially intended as a ‘bootstrapping’ exercise to teach swabbing techniques, interest in the data inspired a Microbe Map visualization. More recently, the group is breeding snails to select for certain traits.

So far, we have shown that DIYbio is closely aligned with pre-existing hacker cultures by embracing tinkering, creating play and open access to science outside of professional settings. At the same time, individuals with professional biology backgrounds form the core of this community, from sharing technical knowledge through DIYbio.org, to advising on safety procedures or engineering new materials such as the *Bacillus subtilis* plasmid. DIYbio thus creates a hybrid space for professionals and non-experts, and emerges from the discourse at this intersection. Inspired by the interplay between synthetic biology and ‘open source’ values, this space supports “*new ways of science-making*”, including

bioart, biohacking and citizen science, which do not exist *inside* or *outside* of professional biology but *within* it [24].

MATERIALS

The materials used by DIYbio practitioners—both to conduct experiments and to experiment on—also tend to merge professional and DIY domains. For instance, DIYbio labs were found to exploit the broader developments in biology R&D. Biotech companies upgrade or relocate, and institutions receive funding to purchase new equipment, resulting in a large turnover: from microscopes and incubators, to glassware and chemicals, materials are being discarded or replaced. Each DIYbio group had its own ways to take advantage of this situation. Genspace inherited a range of tools and chemicals from a closing biotech company, much of Bosslab's equipment was donated by a university, Indie Biotech acquired glassware from a local charity, *etc.* It's notable that while many of our participants described donations as easy to find, others worked hard to establish relationships with local facilities. For instance, Dr. Ellen Jorgensen, one of Genspace's founders, has served as the primary liaison between Genspace, New York's universities and biotech companies.

In many cases, DIYbio groups also spoke of having to circumnavigate institutional policies. Certain materials such as primers, dyes and cell cultures are necessarily purchased from biotech distributors. However, larger suppliers cater almost exclusively to professional laboratories, forcing DIYbio groups to find ways to register as legitimate organizations with the suppliers or to order from smaller companies. As Bosslab's founder explains below, his lab's website serves as an important resource for gaining credibility in such cases:

They'll [biotech distributors] call you and find out if you're a real business. Like my lab had a sketchy website a year ago I think that the new website like helps out a lot cause they do like take the your name and your email when you sign up to see who you are a lot of times.

With the acquisition of materials, then, we found the links (as well as separations) between DIYbio and professional biology to be further reinforced. The thing we found especially remarkable here, however, was not only the mixture of amateur and professional expertise, but also the mixing of the materials themselves. While some materials are cheap and easy to come by, others pose a challenge for DIYbio labs and thus inspire opportunistic attempts at homemade or repurposed assemblies.

Manchester DIYbio is collaborating, for instance, with the Arduino hacking group to design their own PCR machine⁴—a thermal cycler for replicating segments of

² <http://www.nanoinfobio.org>

³ <http://www.wellcome.ac.uk>

⁴ Polymerase Chain Reaction (PCR) replicates specific strands of DNA (*e.g.*, genes) by applying temperature cycles to a mixture of DNA, primer and polymerase bonding agent. Gel electrophoresis can be used to visualize the resulting DNA segments by applying an

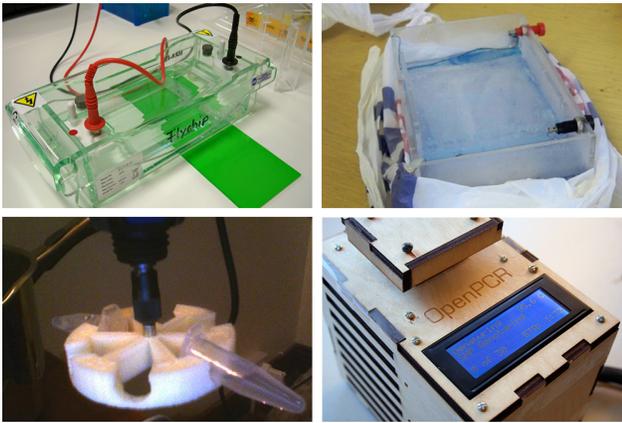


Figure 2. Gel electrophoresis box in a professional lab (top left) and assembled from scratch at London Hackspace (top right); Dremelfuge developed by Indie Biotech, image source www.indiebiotech.com (bottom left); OpenPCR kit for replicating DNA (bottom right).

DNA. Similarly, the London biohacking group has used a combination of crude electronics and laser-cut casings to construct a *gel electrophoresis box* (Fig. 2). In addition to this homemade equipment, off-the-shelf products are also repurposed, often in simple ways. Examples include: a pressure cooker, used for sterilization and as an autoclave in Bosslab; snails from a pet store in DIYbio Manchester’s breeding project; a bioartist experimenting with green tea as an antibiotic; a pet heater and thermostat from a pet store as Indie Biotech’s incubator, and many others.

While such assembly and appropriation also occurs in professional settings, the DIYbio community appears to approach their interactions with materials differently. At professional labs, we found repurposing to be the easiest or only way to obtain a material. An iGem team we spent time with, for example, was relying on supermarket squid to study iridescence. Another professional biologist we spoke to uses products from local supermarkets in his lab to avoid being ‘ripped off’ by biotech distributors.

Despite sharing this interest in handmade and repurposed materials, the DIYbio groups appeared, uniquely, to see such practices as an end in themselves. All participants spoke of adopting others’ designs and sharing their own through online forums. BiologiGaragen and Indie Biotech placed a particular emphasis on creating and sharing affordable tools, with the former building a shaking incubator and the latter selling the *dremelfuge* and developing a new DIYbio plasmid, as discussed earlier. Numerous similar initiatives have also led to the availability of low-cost kits for purchase and assembly:

- OpenPCR—a DIY, Arduino-powered kit for performing PCR to replicate segments of DNA [34]

electric charge across a gel, causing smaller bits of DNA to travel further (faster) than larger ones. A tutorial we found most useful can be seen at: <http://www.dnalc.org/resources/animations/>

- Pearl Biotech—gel electrophoresis box for hobbyists and scientists [37]
- LavaAmp—a pocket-sized hardware platform for PCR, created by biologists, engineers and philosophers [29]

These early innovations have inspired a range of ongoing projects: the ‘Lightbulb PCR’—a thermal cycler made from a lightbulb, an old computer fan and an Arduino⁵; an iPhone microscope modified with a \$5 lens from Amazon⁶; and open source orbital shaker using Arduino and stepper motors⁷, to name a few.

Hybrid assemblies

DIYbio’s work with *organic* materials introduces a unique set of issues and challenges. The improvisations and combinations often result in hybrid assemblies that are different from the digital materials usually worked with in HCI. Below are four issues associated with this hybridity that emerged as especially salient in our research:

Storage: Chemical and biological samples often require specific storage conditions (temperature, light, humidity, etc.), and living organisms depend on nutrients, light cycles and other care. Also, when working on hybrid solutions, it is necessary to determine how the organic materials are sensitive to paints, acrylics, FDM, and other plastics. Even with bio-friendly enclosures, there are issues of sterilization and contamination, not to mention questions of biosafety; as a Genspace founder emphasized, “*we didn’t want to put transgenic organisms in the same fridge where people put their soda pop.*”

Transport: Closely related to the above, DIYbio faces a range of transportation issues, from the physical logistics of packaging and maintaining environmental conditions in transit, to the biosecurity regulations of importing and exporting organisms. This often means hybrid assemblies require inbuilt solutions for supporting safe mobility.

Disposal: Professional organizations have infrastructures or departments dedicated to handling bio and chemical waste. As Bosslab co-founder points out, individuals often do not have access to such resources: “*there’s no like straight forward answer to a lot of safety questions such as can I pour this down the drain*”. Workarounds include DIY autoclaves, as well as employing professional waste disposal companies. The assemblies themselves also require ways of accessing and removing waste.

Time and uncertainty: Hardware and electronic materials are marked by precision and speed, while organic processes operate on slower and often less predictable timescales. For instance, it might take days to culture a cell colony, weeks to grow an algae population, or months to

⁵ Lightbulb PCR. <http://vimeo.com/18827627>

⁶ Crabfu \$5 iPhone Microscope Mod <http://crabfuartworks.blogspot.com/>

⁷ Open Source Orbital Shaker <http://www.thingiverse.com/thing:5045>

breed snails. Hybrid assemblies raise the challenge of coordinating the usual speed, accuracy and efficiencies of electronics with these far less predictable counterparts.

PUBLIC ENGAGEMENT

As a movement to ‘open source science’, DIYbio is fraught with initiatives to broaden participation in hands-on biology. However, by working with living organisms, DIYbio must also navigate a host of public concerns, from ethical issues to legal regulations. Below, we outline a few key intersections between DIYbio and the general public.

Active participation in science

Our DIYbio participants almost unanimously shared visions of wider participation in science, ranging from more people working in DIYbio labs to individual science experiments at home. DIYbio communities host a variety of efforts to this end: Genspace runs weekly courses that cover synthetic and molecular biology; BioCurious is planning a range of classes to teach basic techniques—pipetting, PCR, *etc.*; and nearly all groups organize workshops with hands-on science components, such as DNA extraction and electrophoresis.

While these initiatives tend to be well-attended, they often fall short of inciting sustained participation beyond each event. The founder of BioCurious attempts to explain this:

Some people had gone to class to take a biotech course but after the fact, all the people there were professionals in some other field... and they didn't know how like they could play with science like: 'I don't even know what the next experiment I might do is'

As suggested by BioCurious, newcomers to DIYbio seek guidance and inspiration for projects, beyond the technical knowledge acquired through classes. Another deterrent is the form factor of lab equipment, which according to one DIYbio participant, can appear “*so professional and so scary and complicated*” to beginners. Thus, DIY groups focusing on synthetic biology and wetlab experimentation still lack a body of ‘hello world’ examples and tutorials to afford easy entry into day-to-day practice.

Public concerns

Not surprisingly, our participants encounter varying degrees of skepticism and fear when presenting DIYbio.

We presented DIYbio at Future Everything, a big art festival, which was great. We showed different projects we are talking about and where DIYbio is at, and it came to the questions. First question was bioterrorism, like this stuff looks terrifying.

The above quote from Manchester echoes many of our participants’ experiences whereby DIYbio raised concerns of bioterrorism and safety. Consequently, DIYbio adopts several strategies to address and negotiate these issues.

From biosecurity to biosafety. First and foremost, DIYbio groups aim to shift the discussion from biosecurity (*i.e.*, bioterrorism) to biosafety—practices that ensure safe use of organic materials outside institutional settings. For

instance, numerous groups in the US (Genspace, BioCurious) work in BSL1-certified labs, while others are advised or led by professional scientists. Furthermore, after several overly-aggressive attempts to regulate DIYbio, the FBI adopted a ‘*community watch*’ approach. As part of this program, the FBI meets with DIYbio groups to discuss safe practices and mediate concerns between the labs and the general public.

In Europe, regulations around DIYbio are less established and further complicated by the ongoing debates around GMO’s. Indie Biotech acquired the first individual license for working with genetically modified organisms to “*equip myself with the law and to stay on the right side of it*”. Other European groups follow this philosophy, for example: “*we haven't been certified at the GMO level so we will not violate that in any way*” (BiologiGaragen⁸).

Codes of ethics. Recently, DIYbio.org initiated several events (“continental congress”), whereby representatives from local groups convened to draft a “DIYbio code that may serve as a framework for helping us achieve a vibrant, productive and safe global community of DIYbio practitioners”⁹. In addition to building consensus around best practices, the code serves an outward-facing purpose:

Here we have a code, look at our code. This is who we are, this is what we do and furthermore when someone does something stupid or wrong or illegal then we can say look at our code, that's not DIYbio, please don't call it DIYbio.

Above, the founder of Indie Biotech explains that the code is intended to define DIYbio as a safe and ethical community, distinguishing it from people who work outside accepted practices.

Transparency. In addition, our participants emphasized transparency as the key approach for addressing public concerns. Lab activities are photographed and published on blogs, websites and wikis, and day-to-day events are broadcast through social media (*e.g.*, youtube, twitter).

I think we do that pretty well here by being absolutely transparent with everything we're trying to do. So if anyone wants to see what we're up to, just go and look at this photo stream and you'll have a pretty good sense of what's happening.

Above, the founder of BioCurious describes a public photo stream as a mechanism for sharing work with the outside world. Similarly, Bosslab has a camera that automatically uploads all images to their flickr account, as well as DIY sensors that post the temperature and status of key lab equipment to their website.

We have thus presented several interesting ways by which DIYbio relates to other stakeholders. Many initiatives

⁸ From a phone interview with Martin Malthe Borch, M.Sc. Biological Engineering, August 1, 2011.

⁹ <http://diybio.org/codes>

invite members from the broader public to participate in science. Others serve to mediate bioethical concerns, referencing the general public as an audience. These bioethical tensions are negotiated within local DIYbio groups, the larger DIYbio.org community, and across a range of stakeholders—from law enforcement officials to members of the general public.

INTERSECTIONS AND SEAMS

As a consequence of its motivations, challenges and practices, DIYbio has created an array of complex intersections: i) it draws on existing hacker practices and values while also collaborating with professionals; ii) the materials are often hybrid assemblies of living organisms and digital technologies; and iii) it references the general public as active participants and a concerned audience.

In the remains of this paper, we want to give thought to a more general but, we hope, still constructive way of orienting to the area—with the intention of opening up opportunities for HCI. The framing we found particularly useful has been one of designing across *seams*, those points at which different materials, practices, categories, *etc.*, intersect, sometimes in unexpected ways. The biology-machine intersection is itself such a seam, of course. Yet we see other compelling juxtapositions if we consider the reported bio-electronic materials, such as the Arduino-controlled PCR machine for replicating DNA or a shaking incubator that uses servos to culture living organisms. On a higher level, DIYbio operates at the fringes of professional science and hacker subcultures, while also intersecting with the general public.

This recognized value of intersections is closely associated with Chalmers', *et. al.* ideas surrounding seamfulness [7] and the discussions of categories and boundaries from Bowker and Star [3]. Both perspectives talk of seams or boundaries as generative, not things to be necessarily covered up, but junctures that lend themselves to new ways of seeing. For instance, Chalmers, *et. al.* celebrate “undesired seams” in a network topology as a rich design space. Swan *et al.* similarly identify those spaces where things fall between and betwixt as ones that allow for conventions to be disrupted and alternative ways of ordering and knowing to be produced [44].

To explore the intersections emergent in our research, we constructed three design exercises we see as operating at the seams. All three prototypes are fully-functional devices, built using the Gadgeteer .NET platform [32] and FDM 3D-printed enclosures. We present these artifacts as design probes to prompt critical reflection on the role HCI might play across some of DIYbio's complex intersections. This approach builds on prior work in HCI where construction of artifacts productively raises questions and opens new design opportunities for future work [e.g., 16, 19, 40]. It's worth reiterating that the point here is not to present our prototypes as solutions to

specific DIYbio problems, but instead, as examples of how working at the seams can be fruitful for HCI.

Exercise 1: DIYbio and professional biology

DIYbio has intentionally positioned itself as a movement outside of and in some ways opposed to professional biology. From its motivations (to ‘open-source’ science or unsettle institutional power structures), to the aesthetics of tinkering with organic materials and its close associations with existing hackspaces, DIYbio's agenda is not one of academic research. At the same time, the lack of ‘how-to’ examples for beginners and the complexity of the science, its equipment and surrounding ethical issues necessitate biologists to remain at the core of DIYbio.

This tension—of being set apart yet being closely in touch with professionals—inspired our first design exploration. Currently, communication between practitioners with varying degrees of expertise is mediated by online forums and blogs, or through advisory boards as in the case of Genspace and Manchester. To open this space beyond computer-mediated or in-person interaction, we developed a screen-based, wifi-enabled device that looks not unlike a petri dish (Fig. 3). In our exercise, it was programmed to display messages from the DIYbio Manchester's mailing list to be viewed by professional or DIY biologists in remote laboratories. Opening the lid and tilting the “petri dish” toward oneself activates the screen, and tilting it left or right advances the content backward or forward.

On the face of it, this object explores something that probably isn't a major problem for biology practitioners; after all, most are astute internet users. However, the design and subsequent discussions prompted us to consider location, cultural practices, and form factor for communicating information within a biology lab (whether that be someone's garage or a traditional laboratory). Inspired by the physical aspects of labwork, the form factor of our device mimics practices of examining a sample in a petri dish. How might form factors influence professional and DIY labs to critically examine *each other*, and what kinds of new benefits or complications could arise? In this way, the device also prompted questions about boundaries between the wider DIYbio community, the physically delimited professional and DIY labs and the work within them. For instance, how can information be shared more fluidly across physical settings while also sensitively supporting cultural differences between professionals and hobbyists?

The exercise also drew attention to the way new ideas might be introduced as sources of inspiration and creativity—again, two aspects we found as central for DIYbio. For example, our prototype is designed to sit alongside other biological instruments and be casually handled, perhaps allowing for discovery in the midst of routine activities (such as pipetting). Similar devices might be situated in labs to display SMS questions, answers or ideas for future projects. The seam here, then, might be not

only at the intersection between professionals and DIY'ers, but also between the routine and extraordinary. The broad opportunity for HCI appears to be one of imagining new ways for these to intersect: how can extraordinary ideas be shared in routine practice; how can routines across different labs be coordinated to support collaborative tinkering, play and innovation?

Exercise 2: DIYbio and the general public

Our second exercise explores relationships between DIYbio and the broader public. Again, this seam is fraught with tensions: DIYbio encourages people to participate in 'hands on science' through workshops, classes, *etc.*, while also navigating the many public concerns regarding its practices. Its outward-facing efforts, from a code of ethics to mechanisms that make lab work more transparent, publically address questions of safety and ethics.

With transparency as a key value for DIYbio, we designed a GPS/SMS-enabled touchscreen device, not unlike a microscope, for viewing and sharing organic processes. A petri dish can be placed on the device, and a camera mounted above magnifies and displays its contents on the screen (Fig 3.). Images can also be stored on an SD card or shared via SMS along with the device's GPS location. In our example application, images are saved every ten minutes and can be viewed as a time-lapse video of the biological process. The record and play functionality is invoked through a menu on the device's touch screen.

In constructing this artifact, we uncovered a range of design opportunities at the intersection of DIYbio and surrounding public issues. On one hand, DIYbio practices—culturing swab samples (*e.g.*, Manchester's Swabfest) or growing a colony of model organisms—can

be made more transparent by broadcasting progress, location and other metadata to websites or public displays. Alternatively, public-facing tools such as our device might be re-appropriated to express other types of information, for instance requests for materials, and connect with providers (local charities or bio tech companies) that might be able to donate them. Our prototype also speaks to DIYbio's goals of involving more people in biology: similar devices might be adopted as scaffolding tools to support independent biology work. For example, more experienced practitioners might annotate biological processes with metadata that teaches beginners how to safely run similar experiments in their homes.

More broadly, this design exercise suggests leveraging common scientific instruments (*e.g.*, microscopes) beyond observation and data collection. At the very least, foregrounding interactions with such tools in DIYbio and professional settings can demystify lab practices and involve a range of stakeholders in scientific discourse. This raises a host of questions of HCI: from the practical considerations for fluidly attributing metadata (*e.g.*, GPS, time or care instructions) to organic processes; to the mechanisms for sharing this information with stakeholders such as novice practitioners, law enforcement or the wider public; to the higher-level implications of mediating dialogues across these groups. The seam—across DIYbio and its various stakeholders—presents opportunities to rethink hardware platforms (*e.g.*, microscopes) as instruments of public debate and in turn re-envision modes of science making beyond DIY and professional labs.

Exercise 3: Hybrid materials

Our final exercise focuses on the hybridity of DIYbio materials. Common electronics—Arduino, sensors, servo motors, *etc.*—are combined with more professional lab equipment to culture, study or modify organic specimens such as *e. coli*, *c. elegans*, zebrafish or snails. The underlying seam—between living organisms and digital technologies—results in imaginative, innovative and sometimes strange workarounds across issues such as storage, disposal, time and uncertainty.

To gain broader insights into working with living organisms, we designed an interactive device for viewing bioluminescent algae (*pyrocystis fusiformis*). These algae emit a blue-green light when mechanically agitated (*e.g.*, shaken), but require a resting state between each stimulus for the shaking to have noticeable effect. Our device is thus made up of a glass vial of algae attached to a servomotor, all encased in a dark container with a small hole for viewing (Fig. 3). An external trigger (for the purposes of this exercise, a button) oscillates the servomotor, shaking the algae. After each actuation, luminescence is measured with a light sensor that has been calibrated for blue/green wavelengths and presented on a small display below the vial.

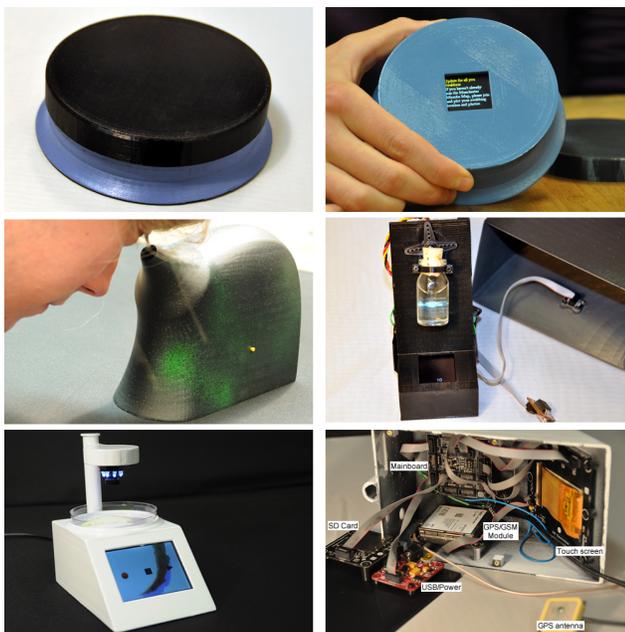


Figure 3. Design exercises: interactive petri dish (top), bioluminescent algae shaker (middle), GPS/SMS-enabled microscope (bottom).

Despite its simplicity, we found this prototype to raise some unexpected issues. For instance, the delay required between shaking the algae led us to build a counter into the display to indicate when the device is ready to be used. Also, since the algae depend on a 24-hour light/darkness cycle, after each demo, specimens had to be stored in a dark place with timer-controlled lights. The need to consider these issues illustrates that the qualities of living organisms (time, storage, care, *etc.*) demand, perhaps predictably, very different approaches to interactive system design. In our exercise, we wondered how new designs could exploit the delay between actuation and the somewhat theatrical quality of having to peer into a darkened container to view a dispersed luminescence. More generally, we were left to ask, might there be benefits to designing technologies that mimic living qualities, such as being slower, less predictable and more reliant on our care?

In addition, our exercise suggests a range of possibilities for novel bio-electronic configurations. In the context of HCI, prior work has already suggested incorporating living organisms (biomarkers) as inputs in environmental sensing systems [27]. In addition to these pragmatic (*e.g.*, citizen science) applications, we argue for more broadly exploring bio-electronic assemblies as new materials for HCI. As visionary hybrid technologies such as the Lilypad [5], which merges textiles with electronics, or Skinput [18], which proposes computing on the human body, continue to advance our field, we ask, what are the implications for HCI when organic materials are integrated into interactive systems? To be clear, this is not a speculation on a far-away science fiction future: a number of low-cost kits that use electronics to manipulate organic materials such as DNA or bacteria are already available for purchase [34, 37, *etc.*], while many other combinations are being designed and assembled in DIYbio and professional labs around the world. What then are the challenges, and more importantly, the outcomes of these emerging hybrids, which leverage living organisms as inputs and outputs, and how can HCI contribute to their development?

By operating at the intersection of digital and organic, and at the seams across professional, amateur and public, the DIYbio movement might offer valuable insights. At the very least, our findings suggest several direct points of engagement for HCI, for instance: bio-electronic “hello world” examples for *‘playing with bio’*, such as our simple algae device; electronic platforms that can be more easily interfaced with living organisms (*e.g.*, Arduino shields that maintain specific light and temperature conditions for culturing certain organisms); technologies that support “sketching in bio”, similar to Sketching in Hardware, for quick prototyping of bio-electronic systems; as well as new infrastructures for working with organic materials, including assemblies for storage and transport, and tools that support safe disposal.

On a higher level, the convergence of biology and computation presents a rich design space for exploring bioethics. Our algae device, for instance, intentionally and provocatively juxtaposes each bioluminescent event with a digital light sensor value. This design decision, whether appropriate or not, aims to foreground tensions between the organic and digital by expressing a fluid and rather beautiful natural quality as a precise number. Future work can focus on bio-electronic assemblies that overtly reveal and even exaggerate similar issues, from the ethics of manipulating living organisms (for instance, by pressing a button to stimulate algae) to the philosophical questions of reducing living entities to simple inputs and outputs that are treated as parallel to digital sensors and actuators. Such hybrid artifacts might serve as boundary objects, *materializing* ethical concerns to engage biologists, hobbyists and members of the general public in productive discourse around the future of biotechnology.

CONCLUSIONS

We presented DIYbio as a growing community of individuals and groups that coalesce around tinkering and experimenting with biology outside professional labs. Its unique practices result in complex intersections across stakeholders, materials and concerns. To reflect on HCI’s role across these *seams*, we presented design exercises to explore three areas for future research: *internal collaboration tools* within the DIYbio and professional community; mechanisms for *external communication* with stakeholders from the general public; and *bio-electronic assemblies* of organic and digital materials.

More broadly, we hoped to show that the particular properties of biology, and its convergence with electronics and DIY practices, invite questions for HCI around generative hybrids, and seams or intersections. We see that a specific concern for intersections, especially in DIYbio, offers a way to start thinking openly about new design possibilities. For instance, the various ways of seeing the divisions between DIYbio, professional biology and the public offer opportunities for designing at these intersections. Likewise, the points of intersection between the biological and electronic open up opportunities for imagining new hybrid technologies. Our design exercises operate at the seams, much like DIYbio does, to offer initial and modest attempts at designing in and for these junctures. We hope our work inspires future research at the emerging intersections between biology, computation, DIY and public discourse.

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