Tools for Biomakers

Reviewing Affordances and Challenges for K-12 Hands-On Making with Biology

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ABSTRACT

While many digital or physical tools and construction kits have been developed for young makers, far fewer developments have focused on making with living materials, at DNA and cellular scales. In this paper, we review the affordances of various hands-on simulation tools and wet labs for K-12-aged biomakers to be used in school, home and science centers. We discuss how making with biology requires broadened conceptualizations of perceptibility, tinkerability, expressivity, and usability—features commonly considered in the research and design of digital and physical maker media. We conclude with a discussion of affordances and challenges we see in the current generation of tools and labs for supporting making with biology and in which ways these can be expanded to support learning, collaboration, and creativity that are valued in maker education.

CCS CONCEPTS

• Hardware → **Emerging Technologies;** *Emerging Interfaces*

KEYWORDS

Biomaking; Biology design; fabrication devices; K-12 education

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1 Introduction

The Paralleling the DIY and Maker Movement, the last decade has seen a significant growth in biotechnology applications and tools promoting a paradigmatic shift in biology: from a natural science primarily concerned with observing and understanding the laws of nature toward a design science where this understanding is used to create and engineer new materials and applications. This shift toward design supports "hacking and tinkering with biology" [1] much like the DIY or maker movement engages young learners in hacking and tinkering with electronics and other inanimate materials [2]. In biological design [3]—or making with biology—users make genetic or other modifications to biological systems to create novel and sometimes unpredictable outcomes. To do so, they use DNA, that is now available in standardized parts, to deliver genetic information. This DNA in standardized parts is sometimes referred to as a BioBrick [4], an explicit reference to the LEGO brick. Observing these developments has led a recent maker educator [5] to predict that "grow is the new make."

But growing or making with biology is also quite distinct from making with digital, physical or hybrid materials that are commonly used in maker education [6]. For instance, all manipulations of genetic materials happen in liquids, and are not immediately visible, sometimes requiring several hours (if not days) to grow or develop due to constraints such as a cell's biological functions. Furthermore, biological processes are irreversible and do not involve readily reconfigurable and replaceable tangible parts. These unique features of making with biology are distinct from digital or hands-on production of usable, shareable, and personally meaningful artifacts—all of which are quintessential to generating interest and motivating learning in maker activities (e.g., [2]). As the world of biological making is becoming accessible to children and youth, we need to understand the various affordances and challenges these tools provide when interacting and designing with living media.

Because biological materials involve reactions that occur on microscopic scales, important affordances include the ways and extent to which these tools represent processes that are invisible to the naked eye. To better understand these differences, we examine them in terms of the extent to which each tool design allows users to engage with features or outcomes that have traditionally been characterized as inherent to maker activities, namely *perceptibility*, *tinkerability*, *expressivity*, and *usability*. Designs that make underlying processes visible or provide immediate feedback to users either on the progress or results of their making promote *perceptibility*. For instance, a computer coder can immediately see the result of a bug they fixed in a program [7]. *Tinkerability* enables learners to explore materials and iterate designs [8]. Tinkering is characterized as a playful, experimental iterative style of engagement wherein makers are continually reassessing their goals, exploring new paths and imagining new possibilities—this process is sometimes characterized as having "a conversation with the material" (p. 165). *Expressivity* refers to the extent to which individuals can personalize or design products that reflect their interests, desires, or needs. It is often considered an important motivator of engagement and learning in maker activities [9]. Finally, *usability* refers to the ability to create designs that can be used as intended and immediately for play, learning, or work. This list of affordances is by no means exhaustive but provides a good starting point to examine tools meant to facilitate hands-on, biological design on genetic and cellular scales.

In this paper, we review tools for making with biology that have been developed in the last five years for K-12 education to address the following research question: How do enabling affordances such as tinkerability, perceptibility, expressivity, and usability support (or not) making with biology? We first describe tools that simulate interactions on cellular or DNA levels (hereafter: simulation tools) and then those which facilitate interactions with living media (hereafter: wet labs). We then discuss how these tools promote interaction and design with living media that have been typically observed in digital, physical or hybrid tools [6, 7, 8]. We conclude with a discussion of the challenges and opportunities we see in the current generation of simulation tools and wet labs for supporting making with biology and in which ways these can be expanded to support interaction, collaboration, and creativity that are valued in K-12 education.

2 Review Approach

The focus on making with biology is a fairly recent direction in research [1, 3, 10] with only few developments targeting K-12 audiences. We conducted a search through science and ACM conference publications and journals that focused on tools that enabled users to design and introduce unique living organisms in virtual environments as well as tools that enabled users to genetically modify cells and then visualize or design unique products. The papers were accessed using Google Scholar and the ACM digital library. Our selection criteria included: (1) designed to facilitate or promote interactions with biological materials at genetic and cellular scales; (2) developed over the last five years; (3) focused on K-12 makers; and (4) for use in home, school and/or informal settings. Searches included such terms as biodesign, synthetic biology, lab kit, simulation, and k-12 learning.

Through this process we identified eight simulation tools and wet labs that covered the range of technologies currently available for K-12 making. While initially we found more simulation tools, these focused on adult expert users [11] and thus were excluded from our review. Furthermore, we investigated whether any kind of usability or evaluation study (i.e., observations, interviews, implementations in different contexts, etc.) had been conducted with actual K-12 makers and reported. This was the case for the five of the eight tools and labs. In the case of two wet labs, Bento Lab [12] and DNA Playground [13], for which such data was not available, but had an explicitly publicized goal for K-12 students, we substituted these with our own observations. In the case of GIY BioBuddies [14], the design of the actual tool kit was created by high school students for other K-12 students; thus, we used their self-reports as information about on learning. These inclusion criteria and selections were determined and applied by both authors until full agreement was reached.

In the next section, we first describe how each wet lab and simulation tool represented the living organisms, cells, or biological molecules such as DNA or protein. We then present how these tools enable users to 'make with biology'—to assemble DNA or protein, analyze or amplify genetic material, grow organisms, or monitor their designs. Note that in many instances we significantly simplify descriptions and explanations of processes and materials to make the interaction functionalities and descriptions accessible to non-biologists; for more technical detail, readers should consult referenced publications. Furthermore, the two authors used available publications and tool descriptions to independently review affordances such as tinkerability, perceptibility, expressivity, and usability using the following definitions: (1) *perceptibility* for how processes or artifacts were made visible and provided feedback; (2) *tinkerability* for how hands-on interactions and iterations were supported; (3) *expressivity* for how outcomes of biomaking could be customized or personalized; and (4) *usability* for whether final artifact could be used for intended purposes. In the following sections, we summarize how these affordances apply to the simulation tools and wet labs assessed.

3 Tools for Making with Biology

In our review, we assess three simulation tools (CRISPEE, SynFlo, and BacPack) which are tangible interfaces developed to support biological design without any living material. We also assess five wet labs (BioBits, Bento Lab, DNA Playground, Biomakerlab, and GIY BioBuddies) that support biological design using biological molecules such as DNA, protein, or living organisms. The following table provides a summary of media, design and interaction features present in each simulation tool and wet lab (see Table 1).

We first examined how the simulation tools or wet labs represented biological materials (e.g., DNA) or something living (e.g., cells or whole organisms).

	Simulation Tools			Wet Labs				
	Crispee	SynFlo	BacPack	BioBits	Bento Lab	DNA Play-ground	Biomak erlab	GIY Bio Buddies
P	✓	✓	✓	✓	✓	✓	✓	✓
T	✓	✓	✓	✓			✓	✓
E						✓	✓	✓
U						✓	✓	✓

Note: P=Perceptibility, T=Tinkerability, E=Expressivity, and U=Usability

Table 1: Summary of media, design, and interaction present in simulation and Wet Lab tools assessed.

We observed that all the simulation tools used tokens as "stand-ins" for interactions with actual biological materials (see Figure 1). For instance, in CRISPEE, [15] elementary-aged learners used blocks to simulate genetic modifications in a firefly. Users then observe those changes using a portable box designed to illuminate just like a real firefly—the organism this tool is meant to represent. SynFlo [11] provided youth with triplets of tokens that represent bacterial cells called Sifteo cubes that are displayed on small digital screens, and tangible objects that represent environmental toxins or biological molecules like foreign DNA. When assembled, users observed on digital screens how their newly designed organisms would behave—such as whether their new organism will resist a given environmental toxin. Finally, BacPack [16] allowed users to genetically modify and thus design organisms with physical blocks called tokens. These tokens represented genes which were coded for characteristics that could be assembled in different combinations. After completing a design, users could then upload their newly designed organism onto a digital environment that was then projected onto an oversized screen that mimicked an aquarium-like environment. This environment was meant to simulate how their organism would respond and interact with other organisms.

In terms of wet labs, BioBits [17] used ready-mixed DNA and protein—just like cake mix—thus eliminating the need to work with any living cells. In contrast, wet labs such as Bento Lab [12], DNA Playground [13], and Biomakerlab [18] involved biological materials (e.g., DNA, protein, or living cells). In theory, users could genetically modify a wide range of organisms but in practice they worked most often with a provided set of DNA and microorganisms (e.g., bacteria or yeast), each customized for the respective lab. GIY BioBuddies [14] provided starter cell cultures (as opposed to DNA) along with such ingredients as a wood-like composite material to grow and build using mycelium (i.e., mushroom roots) and a bioplastic made from a blend of bacteria and yeast found in Kombucha tea and that can be fashioned into usable objects.

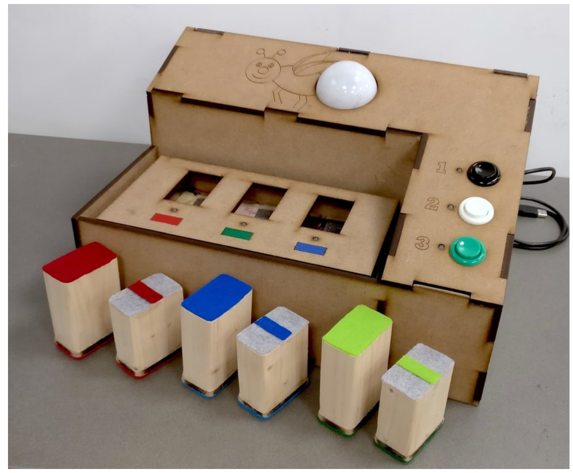

Figure 1: CRISPEE uses a block-based interface to simulate genetic modification. Source: Verish et al, 2018.

Figure 2: Synflo uses digital tokens to simulate genetic modification. Source: Shaer et al., 2013.

Figure 3: BacPack uses an oversized aquarium-like screen to simulate and observe genetic modification. Source: Loparev et al., 2017.

Furthermore, we examined how users engaged with simulation tools to carry out genetic modification. In CRISPEE light color was modified by using colored wooden blocks that could be inserted into a box. After inserting the blocks, users shook it to mimic introducing a genetic modification to alter a firefly's light color. Following this interaction, users then observed the change made via an actual color changing built-in light bulb. In contrast, SynFlo and BacPack allowed users to not only simulate genetically modified organisms but also to see how their designs would interact, respectively, with various materials or organisms in virtual environments. For instance, in SynFlo, students followed a protocol to bring together physical objects (each of which was designed to represent various toxins) with tokens to observe bacterial cell responses before and after receiving foreign DNA (that was coded to include genes that impart resistance to specific toxins). This enabled users to observe how different genetic components or designs affect a cell's behavior and ability to achieve an intended outcome, for example to remediate or resist a particular toxin. In BacPack, users plugged tokens into a digital port and then uploaded the modified design into a virtual ecosystem filled with other organisms represented on a large digital screen.

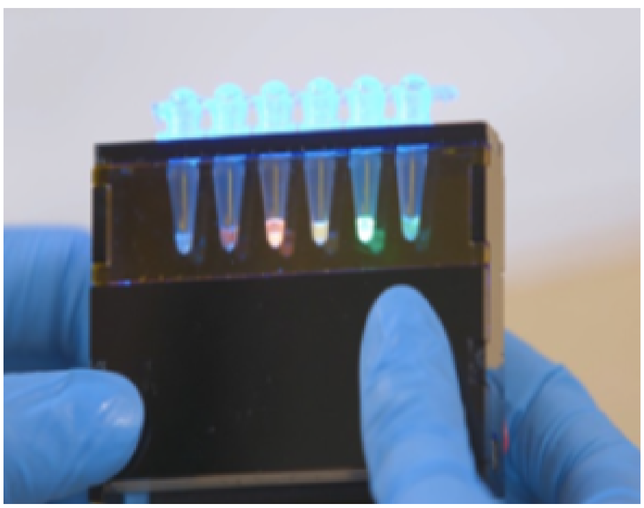

Figure 4: BioBits uses cell free systems to observe biological outcomes. Source Huang et al., 2018.

BioBits users combined actual biological materials (e.g., RNA and Amino Acids or protein) in small tubes (i.e., PCR tubes) to express DNA. After adding DNA materials to each tube and a brief room temperature incubation period, users could observe an array of luminescent colors with a small light box. Users were also able to make an array of fluorescent colors by mixing biological materials in different amounts or combinations. Likewise, in Bento Lab [10] users only amplified and analyzed genetic materials because nothing is grown here. It provided an acrylic container wherein DNA is amplified using a heat source that cycles through hot and cold temperatures (also called a thermocycler) and then separated into individual gene segments using an electric current. Finally, a lightbox illuminates the changes in DNA segments that can later be introduced into an organism. Using a small digital touch screen to set electrical currents, centrifuge speeds, and temperatures, users could isolate, amplify, and analyze DNA. These features enable users to enrich and observe pre-designed genetic materials for use in other wet labs such as DNA Playground or the Biomakerlab.

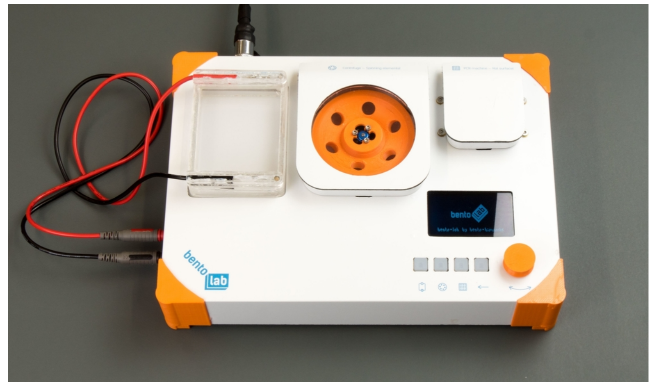

Figure 5: Bento Lab™ allows users to isolate and observe biological materials such as DNA.

Figure 6: DNA Playground™ allows users to genetically alter and fabricate living cells using accompanying protocols.

Other wet labs offered different affordances which were not immediately observable. The DNA Playground [13] lets users genetically modify, grow, and monitor microorganisms but only with a provided (or independently procured) set of DNA and microorganisms that—if correctly assembled—can produce a variety of colors and smells. It includes a heat block which can hold and warm small quantities of cells, a cooling block to slow or stop molecular reactions as needed, and an incubation chamber for growing microorganisms in petri plates, small dishes that contain a nutrient matrix to sustain cells. Users control each of these components via a small digital touch screen to regulate temperatures and set timers for each of the processes. Likewise, the Biomakerlab [18] provided a rotating platform that aerated cell environments to stimulate growth in cell types that have specific oxygen requirements. It also has an encasement to control temperature conditions and a device known as a spectrophotometer, which in the Biomakerlab is used to measure cell replication (i.e., population growth). All digital components and processes are controlled and monitored using a wireless application. Finally, GIY BioBuddies [14] did not provide users opportunities to carry out any genetic modifications, rather it provided starter cultures for users to grow materials and then physically manipulate and assemble them into functional shapes and sizes to ultimately make such toys as dolls, doll clothing, and kaleidoscopes to name a few.

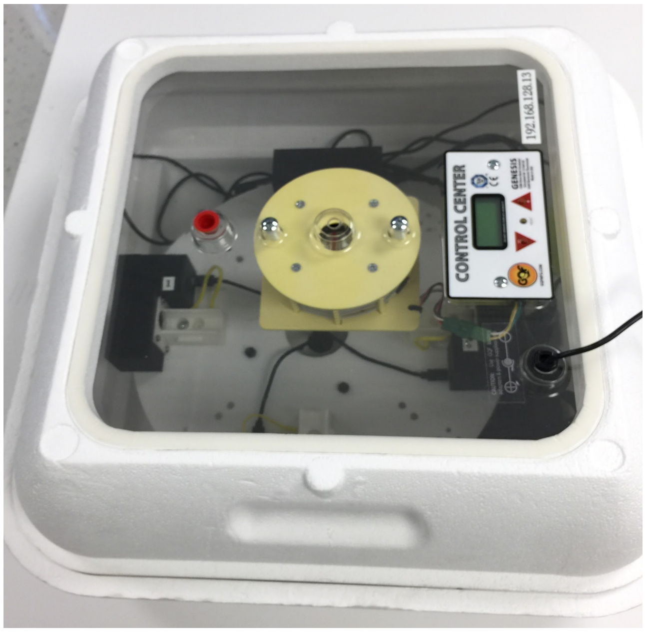

Figure 7: Biomakerlab allows users to genetically alter, monitor, and fabricate living cells for myriad applications. Source: Kafai et al., 2018.

Figure 8: GIY BioBuddies allows users to construct materials using cells (e.g., mycelium or yeast/bacterial mixtures). Source: https://giyBioBuddies.weebly.com/.

3.1 Perceptibility

The one affordance that all simulation tools and wet labs provided was perceptibility, the ability to visualize outcomes and provide feedback about introduced designs. In the case of SynFlo and BacPack, feedback is immediate as digital screens, respectively, provide visualizations that simulate the viability of organisms with particular genetic traits and in the presence of a given toxin or in a given environment. An example is whether or not an organism could survive in an environment if not designed with the genes necessary to impart resistance to a particular chemical. While cell survival or death is an important type of feedback in real biological systems, it only represents one of many outcomes that could result. Some of these outcomes include the presence of a scent when a population of cells has reached a particular growth stage (e.g., quorum) or how a designed biological output is influenced by environmental conditions (e.g., the intensity of a color). Therefore, while these two simulation tools provide important feedback, they are constrained by the extent to which the model represents actual living systems.

A similar point could be made for CRISPEE, which uses wooden blocks as a metaphor for genes and a firefly's light color as the perceivable output. While light color is an important way of understanding whether or not a set of block combinations produces a desired outcome, it is constrained by the fact that the simulation is limited to one attribute (i.e., light color) instead of the many other behavioral and biological features that could potentially be designed (e.g., scent, taste, etc.). Again, this is the result of the extent to which a model or simulation can truly represent a living organism. Still, in basic terms all of these simulations provide perceivable feedback that is immediate and does not depend on organism growth or gene expression, which would otherwise be delayed in actual organisms.

In the context of the wet labs, perceptibility was realized in ways that reflect behaviors of actual biological molecules or living organisms. BioBits represents the simplest system because it does not use actual living cells to generate perceivable reactions. It allows users to introduce biological materials (e.g., DNA or protein) that react in ways that actual cells would. Furthermore, these reactions have short incubation periods and thus feedback is close to immediate. By contrast, the Bento Lab supports the isolation and visualization of DNA, a molecule whose specific genes are otherwise difficult to detect. Therefore, a user can isolate specific gene fragments or combinations of newly designed gene fragments—that can then be amplified and introduced into living systems. Like BioBits, the presence or absence of a given biological material, not actual information related to the viability of a system, is made visible.

DNA Playground, Biomakerlab and GIY BioBuddies all enable users to grow organisms or introduce genetic designs or perturbations to cells directly. The behavior and viability of these cells are readily perceivable over time which provides important feedback about design functionality or viability and in a system that is environmentally and biologically complex. A drawback of these tools is that feedback occurs over a longer timespan (and depends on how quickly cells grow or express genetic designs) and is thus often delayed. Sensors included in the Biomakerlab provide a broader range of perceivability which enable users to quantitatively observe cell growth by measuring the cloudiness of cell cultures. Mycelium and Kombucha health are readily observable visually and by scent and therefore provides more than one way to determine how designs translate into overall outcomes.

3.2 Tinkerability

The simulation tools offered the most in terms of tinkerability due to the fact that they do not involve living materials. This gives users of CRISPEE, BacPack and SynFlo the opportunity to repeat fabrication sequences over and over again within a short time frame. In the category of wet labs, only Biomakerlab and GIY BioBuddies offers users this affordance to tinker because of the range of environmental changes (e.g., temperature and aeration) and additives (e.g., culture nutrients, substrates, and dyes) that can be introduced to support a variety of cells types and growing conditions. As a result, users can mix-and-match different environmental factors (e.g., temperature, the amount of oxygen present, and the amount of nutrient added) in order to test or iterate through a more robust set of designs and outcomes. For all other wet labs, users are required to not only follow a predetermined sequence of steps to assemble designs but also to work with particular materials in order to produce them.

From our own experience of developing activities for the Biomakerlab, we observed that much of the tinkering took place before any students put hands on materials or made anything. Indeed, there were many iterations on failures in the university lab to figure out the right materials and right steps that would result in growing successful colors for students' logo designs [17]. In the case of BioBits, even less tinkering was possible because users essentially did not work with living media at all, instead used what was essentially frozen genetic materials that reacted when mixed or assembled in different combinations. This aspect also increased the chances of success because it removed potential problems that often result when working with living media.

3.3 Expressivity

The expressivity that provides users with the possibility of personalizing the outcomes of their biological designs was an affordance that only few of the reviewed tools and labs provided. In fact, only the DNA Playground, Biomakerlab, and GIY BioBuddies provide opportunities to genetically or physically modify living cells in ways that produce outcomes that can be personally meaningful. Examples include making a color pallet of bacterially-produced pigments that can be used to make personalized designs (e.g., agar art) [9], a biosensor that can detect and respond to molecules in a user's local environment, or toy accessories that can be colored and designed according to user preferences. In this way, expressivity can vary in terms of such characteristics as object color intensity, size and shape. In all other cases, users were constrained by predetermined protocols and outcomes.

3.4 Usability

Finally, usability of designs allows users to leverage biological products to learn, play, or be put to work. Of the tools reviewed, we found that only the DNA Playground, Biomakerlab and the GIY BioBuddies provide opportunities to do this because they are the only tools reviewed here that leverage cells to generate materials that are otherwise not naturally occurring in living systems. Examples include the production of fragrances, pigments, food ingredients, or physical materials that can be used immediately to—for example—make a food product or construct a toy. The GIY BioBuddies tool was the most robust in terms of usability because it enabled users to grow objects for use. Examples include making toy pieces made of mycelium (i.e., mushroom roots) to replace environmentally unsustainable plastic found in many children's toys and then physically manipulating and assembling those pieces into functional shapes and sizes to make toys, dolls, and clothing. For this reason, it was the most maker-like of all tools and wet labs under discussion. While the other tools reviewed here provide usability in other ways (to learn, play or work), those uses are either confined to abstract digital environments or are only useful in biological contexts for technical reasons (e.g., to isolate DNA for future genetic modifications).

4 Discussion

In the discussion, we reflect on what we learned about the affordances of simulation tools and wet labs for making with biology and examine the ways in which this new form of making—with biology—can be leveraged to create powerfully generative and critical engagement. We also discuss how making with biology challenges longstanding perspectives about what is valued in physical and digital making typically found in K-12 education.

4.1 Enabling Technologies for Biomaking

The tools and wet labs included in our review make production with living things more accessible. We need to remember that just a decade ago the process of genetic transformation as described in this review were far out of reach for K-12-aged groups because they required expensive technical equipment and extensive technical knowledge only available in university or commercial laboratories. The tools and labs examined here represent early efforts to make this process available to K-12 makers. This is consequential for children—whose formal knowledge about biology and laboratory skill sets are still forming—because it provides a proverbial "low floor" for entry [6]. This is achieved, in part, because each of the tools were designed to black box processes and phenomena that would otherwise complicate and fundamentally restrict access. This is true for all the tools assessed and illustrative of CRISPEE—that uses familiar blocks to represent how genetic inputs result in varied illuminescent outputs. This is also true of the GIY BioBuddies—that provides starter cell cultures and construction materials that can be readily grown and explored.

We noted that most simulation tools and wet labs made microscopic biological processes perceptible by creating a digital visualization or producing a color or smell. This simple but important way of representing biology helps makers understand

and control their productions, which would otherwise be invisible or overly abstract. Therefore, being intentional about when and how to represent or black box these processes is necessary to create access. Furthermore, these technologies enable makers to engage and explore in ways previously not possible. Examples include observing how genetic modifications are affected by cellular systems or exploring the innumerable ways biological materials can be assembled. It is through these forms of engagement that powerful ideas can be cultivated and expanded like in traditional making.

We also recognize the value of enabling technologies such as simulation tools and wet labs in providing biomakers with opportunities to participate in hands-on explorations that are in many ways shaped by materiality. This affordance was especially evident in our examination of BioBits, Biomakerlab, and GIY BioBuddies, each of which focuses at different levels of production (e.g., genetic, cellular, and cellular outputs). Furthermore, these examples demonstrate the distinct yet ranging paths and styles biomakers can take on when exploring in production. While BioBits eliminates living cells, it provides opportunities for biomakers to pilot genetic materials and biological products such as color and intensity. With the Biomakerlab users can actualize colors using a variety of cell lines and therefore explore how complex organisms (or genetic chassis so to speak) generate (or not) an intended fragrance, color, or flavor. Here, the Biomakerlab provides an important step toward producing usable artifacts that can be explored in terms of and expressed along different perceptive modes (e.g., smell, sight, taste, etc.). In contrast, the GIY BioBuddies kit, which does not emphasize genetic modification, makes it possible for biomakers to use cell products and focus on assembling and constructing usable and personally relevant objects such as toys, games, or jewelry. These features allow users to engage firsthand with materials in different ways.

While these tools provide important insights about how representations and materiality create opportunities for young biomakers to use biology to make and explore powerful ideas and along unique trajectories, we also reflected on what could be produced. In other words, we were interested in understanding what happens when the proverbial floors are lower, and walls are wider [6] with these tools. We found that biomakers generate products that are not only personally meaningful but also critically relevant. The construction kit developed by GIY BioBuddies provided examples for making biodegradable toys that do not contribute to plastic waste and thus addressed climate change and manufacturing sustainability. Their effort also called attention to the value of providing authentic opportunities and contexts for young makers to review and discuss the social, cultural and critical aspects of biotechnology [19]. Therefore, future tool design should consider how to raise the ceiling as to expand the complexity and depth at which young biomakers can critically explore.

4.2 Expanding Perspectives on Making

We started our investigation of simulation tools and wet labs by examining the ways they shared affordances commonly observed in physical or digital construction kits used in maker activities. Like their traditional maker predecessors, simulation tools and wet labs focused on making invisible processes and results accessible to users by providing feedback in form of light, color, smell or other features. But in order to provide this feedback, a considerable amount of black boxing—or hiding what was actually happening on the cellular level—was needed. This use of black boxing is not so distinct from construction kits that involve electronics and that enable users to successfully complete a circuit or execute a program without detailed knowledge of the underlying electronic or computational processes involved. As a result, users are able to engage in a wide range of designs that can be monitored and, even, understood through a range of perceptive modes.

Furthermore, because biological processes are by their very nature irreversible and extended, the lack of immediate feedback leads to different design cycles and forms of tinkering. In other words, tinkering in biodesign is not absent, it just takes place on different time scales and often results in varied or unpredictable outcomes. For instance, when a biomaker is testing whether a particular nutrient source will be suitable to grow a cell, the feedback will include not only whether the organism survives, but also how that nutrient source impacts desired outputs such as smell, color, etc. This is an important distinction in biomaking in that feedback begs attention to multiple variables because cellular systems are complex, integrated, and interdependent, unlike digital materials that often interact in modular fashions (e.g., adding a circuit component does not typically affect the entire project or product).

We also need to realize that affordances such as usability are typically conceptualized as how well a tool can achieve a particular goal or be put to use. Here we broadened the definition of usability to focus on the potential cognitive uses making with biology can provide. In other words, designing an organism in a virtual simulation may not be usable in a traditional or physical sense, but it affords an opportunity for makers to engage in generative production and in service of *understanding* how biological designs function and interact in complex environments. By contrast, products made with construction kits enable users to enjoy not only the processes of making but also the products for play or design.

Finally, we used physical and digital construction kits as reference points in understanding how they render making with biology more accessible to the maker community. We observed how opportunities for tinkering—considered the hallmark of making—were limited with most tools. To make something with biology requires adherence to strict protocols in order to create the right living conditions, thus limiting the "wide walls" or possibilities for making [6]. We also saw that the creation of personalizable artifacts was limited. Of course, we should also ask, what can digital and physical maker activities learn from making with biology? In prior work, we examined more closely the differences between making with e-textiles and biology [9]. We found that the strict protocols for process, or as we called it the processes of assemblage, that are key to success in biomaking can offer an appreciation for working with tools, crafts, and materials. So much of maker education is focused on students producing artifacts as tangible evidence of their learning, that we often ignore that much of the learning is in the process, in the learning of handling the right tools in the moment, and in the learning of nuances in material affordances.

5 Conclusion

This first generation of tools and labs for making with biology is at a similar threshold that making with computers was half a century ago when interactions with the machine were limited to typing code on punch cards. The available k-12 digital and physical construction kits have behind them a long investment in research and development to make interactions more accessible and affordable to young biomakers. Likewise, we need more research on how biotech enabling tools can provide opportunities for learners to interact critically with the world of living media in biology. It is clear that we need to gain further insights on how users tinker and learn with tools, labs, and living media and how to better design affordances that can support further making with biology. Findings from the user tests with CRISPEE, SynFlo, BacPack Biomakerlab, and others indicate that learning, engagement, collaboration and design can be supported across a wide range of ages and in many ways. To make these tools more commonplace in maker spaces, schools and community labs, we need to identify key affordances and challenges, toward ensuring future iterations are leveraged optimally in these spaces.

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