A Revaluation of How We Think about Making

Examining Assembly Practices and Artifact Imagination in Biomaking

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ABSTRACT

While much research focused on making emphasizes digital and tangible media, few studies have explored making with biology, or biomaking, where people use cells as fabrication units to grow or "make" desired materials for designing real world applications. This lack is especially glaring considering how biomaking and related industries are often aligned with a growing push toward sustainable production as a way of addressing the pressing environmental issues of the day. In order address how maker frameworks could be used as a productive way of bringing biomaking into K-12 contexts, we report on the design and implementation of a biomaking workshop where teams of high school students both assembled a physical biosensor and imagined applications for this technology to address real world issues. Using classroom observations, analysis of classroom projects, and focus group interviews, we examined student experiences and perceptions of these activities in order to ask: What the affordances and challenges of biomaking in supporting maker learning, especially with regard to the less common practices of assembly and imagining? In the discussion, we review what we learned about facilitating biomaking in K-12 setting, as well how our analysis led us to a revaluation of the often crucial but neglected role assembly plays in more 'typical' maker activities, and the possibilities for enriching maker activities by including design prototyping and imagination.

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1 Introduction

The growth of the maker movement during the last decade has engaged children and adults as makers in various activities and contexts around the globe [6] providing them with access to production tools and facilities for electronics and hardware previously only available to engineers in research labs or industrial manufacturing. Considerable research has focused on developing construction kits and tools to make games, robots, wearables and many other artifacts, on and off the screen [e.g., 2, 27]. Other efforts have focused on understanding the design of and participation in makerspaces and communities [e.g., 29]. With the growing interest in supporting STEM education, many schools are setting up makerspaces or integrating maker activities into the curriculum [8].

While these developments in making have primarily focused on use of electronic or craft materials and tools, there has been little effort from the maker movement to highlight the increasingly widespread practices of making with biology, or biomaking [15, 33]. Growing out of the academic and industrial field of synthetic biology that emphasizes manipulating (often genetically) biological systems for new outputs [31], biomaking emphasizes the ways in which this process can be leveraged to create design applications that can have practical use in the world [9, 32], whether lab-derived leather or biologically-grown cement. Though advocates of the maker movement have pushed personal computational and digital fabrication technologies to the forefront of the 'new industrial revolution' people involved in biomaking have emphasized how their efforts will ultimately become as essential in manufacturing, considering how developments in the field are aligned with a growing push toward sustainable production and environmental preservation [19].

These developments suggest that biomaking—even in its nascent state—should also become part of the maker movement in K-12 education. Biomaking has already made inroads in a wide range of spaces, whether formally in university education, and informally in community-focused labs (e.g., iGEM, GenSpace) [7, 20]. However, efforts to bring this into K-12 education have been constrained because of the inherent difficulties of working in this area. Even with growing public access to the necessary materials and tools for biomaking, many potential educators and makers lack the necessary expertise required to fully participate (e.g., knowledge of biological systems and their behaviors). Further, there is often a high bar for entry since the processes themselves are difficult to engage due to the inherent complexity of dealing with living organisms, and irreversibility of these processes themselves. Thus, these particular dimensions of biomaking challenge many of the insights that have been gained in previous research on making, which has emphasized the role of iteration and tinkering, as well as opportunities to creation customized, personally meaningful artifacts as key generating interest and motivating learning in promoting productive making [8, 22, 23].

In order to discuss the extent to which biomaker activities support meaningful making, we here report on the design and implementation of two biomaking classroom activities we conducted with 39 high school students. Biomaking required us to deviate from the normal sequence of 'typical' maker activities where students usually work on a single project from start to finish (i.e., initial idea to final artifact). Instead, we separated this process into *two distinct activities*: first, students *assembled* a pre-determined physical biomaker artifact using prescribed protocols that outlined particular hands-on steps, and then, students *imagined* the design for an original, hypothetical prototype that references known biomaking methods to address some real-world issue using the ideas they learned about through the hands-on activity. Using classroom observations and videos, artifact analysis, and focus group interviews, we examined student experiences and perceptions of these two activities in order to answer the following research question: What the affordances and challenges of biomaking in supporting maker learning, especially with regard to the less common maker practices of assembly and imagining? In the discussion, we review what we learned about facilitating biomaking in K-12 settings, and also discuss how this new sequence of activities might provide a new model for designing maker activities within other more typical contexts such as robotics or e-textiles. Rather than elaborating the distinctions between biomaking and electronic making, we additionally highlight how the assumed 'constraints' of the field also promote new values like assembly and imagination, which should be reconsidered and revalued within the context of maker education and learning at-large. In particular, the promotion of maker imagination—or the ability to apply maker ideas outside one's immediate context to wider real world contexts—is particularly pressing at this moment considering our changing world, with its growing social and environmental challenges.

2 Background

Paralleling the DIY and maker movement, the last decades have seen a steady growth in various biological making applications. Born out of traditional life science and molecular biology lab research, bioengineering and synthetic biology have since grown to impact important areas of society—such as food production and health, whether through genetically modified produce, or biologically-derived medicines [10]. More recently however, there have been more efforts to apply these technologies to a wider array of manufacturing and lifestyle contexts [32],including building construction (e.g., Ecovative, Criaterra) and textiles (e.g., AMSilk, Bioesters) [4]. This interest has not only occurred within corporate or university laboratories [e.g. 30], but also within community labs where the emphasis on DIY (Do-It-Yourself) biology [11] has highlighted how the general public can start to use synthetic biology practices for personal use [e.g., 7].

It is only recently that some of these efforts have been introduced to the larger education community. Most of these have been focused at the college or university level through biodesign classes and majors, and the international student competition iGEM [20], where undergraduate teams work to generate novel synthetic biology-based applications. While there have been early efforts to bring these and related biotechnologies to K-12 learning environments, these are far fewer and often do not provide learners the opportunity to engage first-hand with living materials. One particular effort, "Building with Biology" [21], an effort—through various museums— to deliver activities, materials and resources to engage the general public, including K-12 audiences, with social issues concerning synthetic biology and related biotechnologies. Another program "BioBuilder" has adapted undergraduate synthetic biology-based lab activities for high school environments such as after school extracurricular clubs [1]. While these K-12 efforts illustrate early strides toward broadening access to this field into K-12 learning environments, they are limited to activities that often do not provide learners with opportunities to engage with living materials first-hand or creatively. As a result, these efforts often tend to reflect traditional approaches toward engaging with biology, which tend to emphasize observation and didactic interactions for the purpose of understanding how larger biological systems work. In our work, we adopt a 'maker learning' approach [8, 22, 23] toward biomaking—that is, not only providing hands-on experience with materials and tools, but also how this knowledge can be leveraged for continued design and real world applications.

As mentioned earlier, there are several constraints within biomaking that challenge the usual highlighted features of maker learning. At its most fundamental level, to make is "to build or adapt objects by hand'' [8, p. 4], something which involves both a final *product* and an interim *process*. In terms of product, makers may choose to create an object for numerous reasons, whether "the simple pleasure of figuring out how things work, creating an aesthetic object, or seeking to solve some everyday problem" [22, p. 2]. For this reason, objects are often customized to individual makers, because they represent personal goals and interests [23]. In terms of process, making is most often characterized by tinkering, which can be defined as a "playful, experimental iterative style of engagement with materials", where makers receive concrete, perceivable feedback from their changes and use this for the purpose of "continually reassessing their goals, exploring new paths and imagining new possibilities" [26]. For this reason, tinkering can allow students greater agency in shaping their learning experience [24] unlike step-by-step processes, which are sometimes thought to lead to more passive interaction.

It is difficult, however, to promote these hallmarks of making—personal expression and tinkering—within biomaking. Even with growing access to biomaking materials and tools, beginners often lack adequate knowledge about biological systems (e.g., growth patterns of different strains of bacteria or yeast) and practices (e.g., lab procedures for genetic transformation) to guide themselves within the process [32]. In addition, the actual process themselves are often highly unpredictable due to the nature of living organism, something which adds to their complexity. Whereas more 'typical' making such as electronic or crafts materials can allow for mistakes and multiple iterations, biomaking is especially difficult because of the fact that the involved processes are often slow (requiring hours or even days of growth), initially invisible (due to the scale and colorlessness of microorganisms), and irreversible (unlike programming, which easily allows for iterations in the present-day computing environment). Thus, biomaking processes occur in a holistic fashion—fixing a 'mistake' here often requires repeating an entire procedure and waiting for the result. Compare this with engineering and coding contexts where tinkering can more easily occur because individual processes are discrete (e.g., iterating on a gear mechanism or developing a specially defined procedure). All these factors within biomaking create barriers to quickly modifying aspects of the process for new results—and ultimately the extent to which participants can tinker or create customizable products. While blackboxing parts of the process might alleviate these issues and create opportunities for novices to create personalized artifacts (as they already have within consumer-grade electronics kits) [27], biomaking has not yet reached this point of development within its short history.

For these reasons, biomaking with novices tends to emphasize more *assembly* rather than tinkering approaches in order to produce desired outcomes. Assembly approaches toward making emphasize engagement with predetermined step-by-step processes. While tinkering is often considered the central part of making, assembly is just as important in becoming a competent producer. This is especially true considering long-standing maker contexts, such as craft practices or skilled trade work from carpentry to knitting [28], where apprenticeship involves becoming more familiar with particular tools, materials, and practices over time through repetition [12]. The role of assembly becomes especially important within biology contexts, where training on existing laboratory techniques not only requires step-by-step guidance, but also repeated practice [16, 35]. This aids not only in teaching novices the appropriate physical techniques but also supports their competence in the ability to produce and evaluate outcomes. As discussed in our previous work, our hands-on biomaker activity therefore emphasizes assembly practices rather than tinkering [14].

Because assembly can limit students abilities to experiment and create personalized artifacts, we incorporated an additional design *imagining* phase, where students engaged with real world design scenarios and hypothetical prototyping. As seen elsewhere, design scenarios and related simulations have been useful within K-12 synthetic biology contexts, where interfacing with actual materials have often been deemed too difficult or cumbersome. This includes *BacPack*, an interactive exhibit at the San Jose Tech museum where visitors manipulated bacteria in a simulation in order to promote humans' survival on Mars [13], and *CRISPEE*, a learning interface for early childhood participants for learning bioengineering [34]. Likewise, an emphasis on a design scenario (without the creation of a final, tangible product) is something that has become regular practice within human-computer interaction (HCI) contexts, where users are often incorporated into a participatory 'co-design' process. Here, groups are asked to come together to imagine, rather than build, a product that could fulfill some need in the world [5]. We therefore borrow from these existing approaches (paper simulations, design scenarios) in order to design the biomaking activity. While it draws from a Project-Based Learning (PBL) approach, where students are asked to engage with open-ended problems for the purposes of engaging with academic content in authentic contexts [3], it also focuses on the process of iterative design and making.

Thus, by highlighting practices of assembly and imagining, we deviate away from the typical emphasis on tinkering within maker contexts. What affordances and/or challenges do these atypical maker practices (assembly, imagining) hold for promoting a maker ethos toward biology? Further, what might an emphasis on these practices tell us about the nature of making at-large, and the value system that we normally espouse within the educational maker community?

3 Methods

3.1 Participants

We implemented our biomaker workshop, called *BioSensor*, with two STEM elective classes with a total of 38 students (21 seniors; 18 juniors) at a public charter school in a northeastern city in the United States. In terms of racial/ethnic background, 58% of students self-identified as White, 18% Black, 11% Latino/a, 8% other, and 5% Asian. A team of researchers including the participating teacher (a trained biologist and co-author), and two lab technicians led the two workshops with students arranged in groups with three to five students.

3.2 Design of Biomaking Workshops

In this paper, we discuss *BioSensor*, the second in an ongoing series of workshops we designed for high school students to engage hands-on with biomaking practices. The workshops took place over the course of eight to ten 90-minute class periods (the senior class workshop was extended slightly longer than the junior class workshop due to school schedule changes). While our first workshop, *BioLogo* [9], only emphasized assembly of a physical product, *BioSensor* incorporated an additional imagining phase. As mentioned earlier, this separation of design and assembly is unique since typical educational maker activities emphasize the unified design and assembly of a single final product.

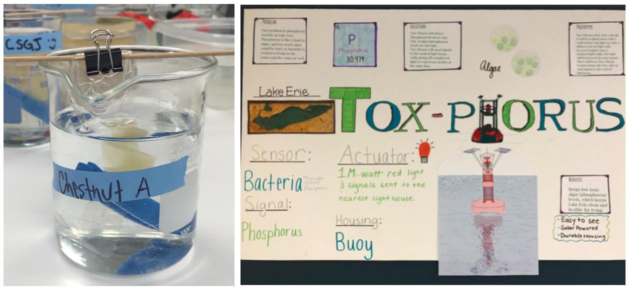

Figure 1. (left) Bacteria-based water detectors that 'glow' in presence of arabinose. (right) Visual storyboard highlighting a biosensor prototype design for detecting toxic phosphorus levels in Lake Erie

In the *Assembly* Phase, students constructed a pre-determined physical artifact, which was a 'sugar detector' using genetically modified bacteria (i.e., *Escherichia coli*) that would glow after detecting a simple sugar (i.e., arabinose) within a small beaker of 'mystery' solution (see Figure 1, top). This incorporated two steps. First, students went through the process of bacterial transformation, which involved inputting foreign DNA into existing E. coli such that it would produce Green Fluorescent Protein (GFP) in the presence of arabinose (a sugar). Second on the following day, student groups followed directions to build a small device that would suspend the modified E.coli in a 'mystery' solution contained in small glass beaker, using given materials (dialysis tubing, wooden sticks, plastic clips, binder clips). If arabinose was present in the beaker, the resulting GFP would glow under an ultraviolet light. Students also spread their modified bacteria into a petri dish with arabinose as a scientific control. This phase was primarily instructor-led, with the two lab technicians walking through the steps of genetic transformation and building the detector with small groups of 2-4 students.

In the *Imagining* phase, students designed an original, hypothetical prototype of an environmental pollutant detector for an assigned real world site in the United States, which would use biodesign processes and products. Students first discussed existing environmental water sensors on the market that used mechanical or chemical parts (e.g., pH sensor, turbidity sensor). Then, in groups of 2-4, they created a design for a biodesign-based detector for an actual water-based site with documented environmental contamination issues (e.g., mercury in Onondaga Lake, acid rain in the Adirondack Mountains). Over the course of 5-7 days, groups iterated upon their designs. Students presented their final imaginary products within a physical 2 x 4' storyboard (see Figure 1, bottom) on the final day to other students, instructors, and a visiting 'expert' judge (juniors only). They also generated a written report to accompany their storyboards. This phase was primarily student-led, with students working in small groups with some deadlines along the way including multiple feedback sessions and the final presentation.

3.3 Data Collection and Analysis

We collected multiple forms of data. For each day of workshops, one to two researchers wrote field note observations and photo documented classroom work. We also conducted focus groups with four randomly selected groups of 3 to 4 students at the end of the workshop, where we asked them to describe and discuss their experiences with both the assembly and design activities.

Our analysis involved several steps. Drawing from our literature review above, we first developed a preliminary set of deductive codes [25] to help define the essential qualities of maker learning (e.g., personal expression, tinkering, agency, hands-on experience, experimentation with ideas, perceptibility of feedback). We then engaged in an initial read through of researcher field notes in order to determine which, if any, of these qualities were actively afforded and/or challenged within the assembly or imagining phases, and in what ways. We documented these preliminary findings within researcher memos [18], and developed a list of these supported/hindered maker qualities, which we then coded for within the focus group transcripts for the purposes of triangulation. Following, we engaged in "connecting strategies" [18], examining both fieldnotes and focus groups transcripts, in order to more clearly understand how these qualities were related to the separate contexts of the assembly and imagining phases. We report on these findings below.

4 Findings

4.1 Assembly Phase

While tinkering is often assumed to be the fundamental basis of productive making, this phase of biomaking activity emphasized assembly, or step-by-step, practices. There were several affordances of this phase in promoting maker learning. First and most obviously, it provided students with actual **hands-on**

experience with biomaking tools and materials. Students actively participated in the laboratory process of genetic transformation, which not only involved tangible engagements with the living materials themselves, such as E.coli and plasmids, but also the tools of biological lab work including cuvettes and hot water baths (see Figure 3, top). As they expressed during the focus groups, students liked this experiential aspect of the workshop since, as Giulia states, it gave them "something we can do". Daria further adds: "I just thought the whole process was fun, because I like doing hands-on stuff... I find I learn a lot better when I'm hands-on too". Milo additionally speaks to the actual process of manipulating microbes itself: "I enjoyed like the specifics…[of] mess[ing] around with the bacteria and all that". This is especially striking because, as mentioned earlier, biomaker tools and materials are often not commonly accessible to people who are not involved in academic or corporate research or community labs that emphasize DIY biology. Thus, students were not only exposed to the context of biomaking, but actually engaged hands-on with creating a new biomaker artifact.

The assembly phase also provided **easy point of entry** for these biomaker novices. Students were given a lab procedure worksheet with photographs and highly detailed directions such as: "Aspirate 3mL L broth into syringe." While this could be seen as a top-down approach, they were guided through each step by two lab instructors, who continually had active discussions with students about the intended result from each step of the procedure (field notes, 3/13/17; 3/14/17; 3/17/17), thereby ensuring a kind of bottom-up tangible interaction with the tools and materials. Because of these supports, students had a relatively easy time jumping into, and thus understanding, the process: "It was pretty easy to understand and we could just get it done" (Geovani); "I thought it was fun because I understood what was happening" (Charaya). While some students complained that this ease of entry meant that it was "dumbed down" (Sanaa, Josie), they still admitted that it was necessary because "I can't go out and do it by myself" (Josie). Considering how these materials and practices are more distant from students than 'typical' maker materials (e.g., programming on an iPad, or glueing together pieces of wood), this ease of entry was key in getting students involved in biomaking.

Finally, the assembly phase also provided a '**proof-of concept**' for students, where students were able to receive concrete feedback and outcomes resulting from their direct actions. Here, this involved seeing that bacteria could be genetically manipulated so that it would produce a glowing substance (GFP) in the presence of a sugar (arabinose). All students were involved in looking at this outcome—at first, examining the lab instructor's control petri dish for fluorescence under a UV light, and then checking on their own arabinose detectors and individual petri dish controls. Unfortunately, none of the actual dialysis bag artifacts that groups creating during this phase worked due to issues with water (it was discovered later that there were a problem with using distilled water and the strength of the bag clips over longer periods). However, a number of students' control plates glowed since they contained arabinose. From this, it was possible for the students to see that manipulating the bacteria for this glow was possible, something that Geovani commented "was fun to see." Beyond this however, students also saw a tangible result from their transformation, something which actively demonstrated the proof that genetic manipulation could work, and the idea that in biomaking, "anything's possible" (Josie) and "we can manipulate anything and everything" (Charaya).

Despite these affordances, this assembly portion also created many challenges for learning through making. This mostly occurred because all students were asked to create exactly the same thing to ensure that would all have a successful outcome (which admittedly, still did not occur due to the finicky nature of biological processes). As to be expected then, one significant challenge to maker learning was the **lack of student agency** in terms of controlling their experience and direction of learning. That is, students were required to follow the instructors' schedule, activities and goals. Another related challenge was that students **lacked opportunities for personal expression** within their final artifacts. Though the projects varied slightly in terms of how the components were attached to one another (e.g., the length of the dialysis tubing bag, how it was clipped on the bottom), this was less a result of personal preference than students' arbitrary decisions. This was demonstrated, for example, within the classroom when students would continually question the lab technicians about the 'right' way to go through the steps, such as where to clip the bags or how to suspend it from the wooden sticks (fieldnotes, 3/15/17; 3/17/17). Thus, while the assembly phase did provide students opportunities to engage with the actual physical process of making, their lack of freedom in doing so could be seen to challenge the 'typical' experience of learning through making.

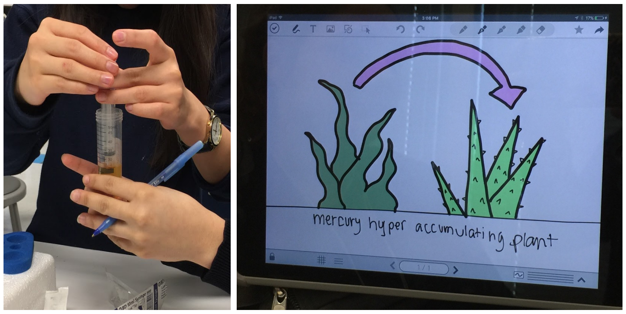

Figure 3. (left) A pair of students adding L broth into their bacteria mixture during the process of genetic transformation. (right) A digital sketch of a plant-based prototype that would change shape after encountering a pollutant.

4.2 Imagining Phase

In order to address the limitations of the assembly phase in promoting maker learning, we developed the imagining phase. We asked students to apply what they learned from the hands-on activity to a real world situation, specifically a synthetic biologically-based environmentally pollutant detector. While not typically emphasized in making, students' abilities to imagine applications beyond their current capacity created several different affordances for maker learning. One of these was that it allowed students to **explore diverse ideas**. While students were all asked to make the same exact physical artifact, their hypothetical ideas varied wildly as they applied the concepts they learned to different water-based environmental pollution conditions. Some groups used the example project as a model; they used genetically modified microbes to sense a particular pollutant (e.g., phosphorus, chromium), which would be held within some physical 'housing' (e.g., porous-bottomed lighthouses, remote-controlled capsules that would sink and rise in water) within the environment (e.g., Lake Erie, the Mississippi River) (see Figure 1, bottom). Other groups went even further with their ideas, choosing to genetically modify organisms other than bacteria. One group proposed an aloe-like plant that would grow spikes if exposed to high concentration of mercury in Lake Onondaga (Figure 4, bottom), while another group proposed seaweed that would change colors in the presence of high petroleum levels in the Gulf of Mexico. One group even presented an idea about a fish-bacteria system, where fish would ingest modified bacteria, and would eventually start to glow after encountering a high concentration of pollutants. Thus, because the activity was imagined, students were not constrained either by their limited knowledge and skills, nor what was possible within their classrooms, and thus able to were able to explore a wider range of biomaking applications.

Another affordance of the imagining phase was that it allowed students to experience **greater agency in shaping their experience**. While the assembly phase required students to follow the given schedule, here students had greater freedom in determining not only the outcome of their projects (discussed above), but also how they went about their design process. At first, students were led through particular steps, including producing two possible prototypes and getting feedback from their classmates. Students could decide whose feedback to use (and whose to ignore), as well as how to iterate upon their their ideas to create their final design. Much of this decision-making occurred through the continual tinkering of their ideas, something that primarily occurred through conversation. For instance, the group who eventually ended up deciding upon the spiky plant to sense mercury ended up choosing between that idea and another more mechanically-oriented design that involved a boat. They worked on their plant idea for several days, discussing the different aspects of the project, including where the plant would be planted in relation to the Lake (i.e., on shore or underwater), how it would indicate mercury concentration (glowing, changing shape), and what other properties it might have (giving off some kind of counteracting chemical after sensing mercury) (fieldnotes, 3/21/17). Much of this occurred within conversations with their team, along with their classroom instructors. Likewise, students also had agency in what areas to focus on within the project. Most groups chose to spend their efforts refining their hypothetical prototype ideas, taking time to draw out different designs and versions (see Figure 3, bottom), something they enjoyed since it allowed them to bring out their creativity (Geovani) through integrating design with science (Layla). Other groups, however, were more interested in learning more about the background of their polluted areas, and spent more time doing historical research about their assigned environmental sites (Camille). Thus, because the project was ultimately hypothetical, students had freedom to focusing their time on topics in which they were more interested, something which ultimately made the students more motivated throughout the process.

Finally, a major affordance of the imagining phase is that it allowed student **consider biomaking within wider real world context**. While the assembled project focused on the artificial context of measuring arabinose in a water beaker in the lab, the hypothetical project required students to consider how to apply biomaker concepts and ideas to actual environmental sites with known issues with hazardous contaminants. Several students spoke about their interest in dealing with real world issues, as Isabis stated: "normally, in our STEM classes,... we never really focused on the environment and what's actually going on in the world, and I thought that was interesting". Along with creating their hypothetical projects, students were asked to research these sites, looking at the history of what caused the contamination, as well as what potential hazards exist as a result. For many, this activity made them more aware of these issues in general, and pushed them into action: "I hope it just brings awareness to people who don't do anything about it" (Aaron); "I think it would be a good idea to actually start making these things [biosensors] and actually see if there's gonna be something wrong in the bodies [of water]" (Giulia). From this perspective, the imagining phase afforded students the opportunity to think beyond their immediate circumstances, and really consider the connections between what they were doing in the classroom and potential applications within the wider world.

While the imagining phase provided these affordances for promoting maker learning, there were also limitations with the activity. Most obviously, there was a **lack of a physical**, **final product** at the end of the process, that is, students were not able to actually construct their hypothetical prototypes. Several students mentioned their disappointment about not being able to see the tangible outcome of their ideas, and wished for more time with the project. Relatedly, another constraint of the activity was the **lack of tangible hands-on experience** with the tools and materials needed for these hypothetical project. Because there was no chance to test out feasibility of ideas, this seemingly limited the students' understanding. For instance, some prototype ideas could not have worked since there was a lack of attention to detail regarding how to keep the bacteria alive in different weather and environmental conditions, or they relied too heavily on mechanical parts rather than focusing on the biomaking aspects of the project. Further, even though the ideas regarding the other organisms were inspired, the process of genetically modifying multi-celled organisms such as plants and animals is much more complex and harder to make work. From this perspective, the imagining phase did create affordances for allowing students to think beyond the classroom in terms of where biomaking could go, but simultaneously also laid the foundation for misconceptions about the practice moving into the future.

5 Discussion

In making with biology, students can use cells as fabrication units to grow or "make" desired materials for designing their applications. The assembly and imagining required within the biomaker workshop illustrated opportunities and challenges for promoting maker learning with high school students. Below, we discuss how our analysis clarifies the logistics of introducing biomaking as a maker activity, as well as how emphasis on assembly and imaging—elements which are typically ignored within digital and physical maker learning—can shift our values about what activities count as making and what can promote productive learning.

5.1 Logistics of Biomaking as a Viable Maker Activity

We already noted the various ways in which biomaking was distinct from traditional maker activities that involve electronics or craft materials. Despite these limitations, our study illustrated the way in which the 'usual' elements of making can be arranged to create a biomaker experience that supports maker learning. Students in our workshop started with construction, and then moved onto design—a sequence that is normally reversed within maker activities. Future biomaker activities could continue to support maker learning by further modularizing and rearranging parts of the process in order to promote different affordances. Students here ended up exactly following procedures to both create genetically modified bacteria for their sensor, as well as building the dialysis bag housing for suspending it within the water beaker. While adding tinkering to this entire process might be challenging, there could be aspects of the process where experimentation could be added, for instance, allowing students to multiple tries to genetically modify their bacteria, each time slightly modifying aspects (e.g., temperature, time) for different outcomes, or creating more opportunities for experimentation in terms of how the dialysis tubing housing could be constructed. Within the imagining design phase, aspects of construction and assembly could be added by allowing students to actually build the physical housing for their bacteria (e.g., mini prototypes of the lighthouses or floating capsules) without actually having to worry about manipulating their microbes. Thus, by rethinking the typical sequence of activities for making (i.e., design, then construction), educators could overcome the challenges presented by biomaking and create opportunities for students to engage with the field.

5.2 The Importance of Assembly in Maker Activities

Our study also illustrated the benefits of promoting assembly practices within a maker activity. The key elements of making are also highlighted within assembly, namely, giving students hands-on experiences with new tools and materials [8], and the creation of a final physical product, along with actually seeing how abstract ideas can be applied for concrete results within tangible applications [26]. Further, assembly approaches provide an additional advantage when considering new or novel maker contexts. Considering how far afield biomaking is to students' everyday lives, working through assembly allowed students an ease of entry into the procedures and processes of the field, something that is exceptional considering the limited access that the general public have to this activity. Rather than seeing assembly in opposition to tinkering then, we pose that assembly works on a continuum alongside with tinkering. By approaching a field with this step-by-step, guided process, students can start to gain greater experience and expertise with the materials and tools, thereby making room for more productive tinkering down the road . This is especially important considering the complexity of biomaking as a process, which, as we mentioned earlier, requires advanced knowledge and expertise to even get started. From this perspective, assembly is just the first step along a longer trajectory to becoming a competent tinkerer and maker [12, 28], and should be supported within maker activities of all contexts.

5.3 Using Maker Activities to Support Imagination

Though numerous maker educators speak about the importance of promoting imagination through making [e.g. 6], many maker construction kits and activities do not explicitly focus on creating space for this practice. Students may imagine a project of their choice, but if they are constrained from doing so by their own lack of knowledge or skill or the inherent limitations of their tools and materials, these pie-in-the-sky ideas have no place within current maker processes. Here, we illustrated the affordances of having students think beyond their current limitations in order to imagine applications for their nascent biomaking knowledge within real world contexts. Students were not only able to imagine wide range of different application forms, but also became more interested in the actual life circumstances in which these applications could be applied. The imagining phase is therefore not just about creating competent biomakers, but also helps to bring students into more expansive conversations about use of these technologies in the real world. This is especially important considering the controversial issues surrounding genetic modification for food and health today [17]. Our students were not only made aware of what these issues are, but were also helped in developing their own opinions about where (or where not) these technologies should be applied. Beyond biomaking though, we believe this imagination-focused activity could benefit the design of other educational maker activities as well. Makers in different contexts—from electronics to agriculture to carpentry—could be tasked with thinking about what real world issues to address with maker tools and materials, whether new ways of addressing environmental pollution or technologies to promote social justice aims. In this way, we can promote students to think beyond the borders of their current knowledge and skill in order to promote more wide ranging perspectives on the role of making, science, and technology in society.

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