Is Making All About Tinkering?

A Case Study of High School Students’ Activities in Biomaker Workshops

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Abstract: Most research on K-12 educational making has focused on tinkering with tangible and digital materials and processes within STEM disciplines such as computing and engineering. Despite the growing fields of bioengineering and synthetic biology, far fewer studies have explored educational making possibilities in these realms. In this study we explore students’ engagement with biomaking, in which people can make new materials and artifacts by genetically manipulating microorganisms. We examined 34 high school students’ experiences and reflections on making biologos by growing color pigments and making biosensors by creating fluorescent reactions. Through observations of workshop interactions and focus group interviews, we found that biomaking primarily engages students with assembly, or step-by-step, processes rather than experimentation or tinkering with materials. In the discussion we address the potentials and affordances of assembly practices in promoting rich learning experiences not just in biomaking, but also in other K-12 maker contexts.

Introduction

The growth of the maker movement during the last decade has engaged children and adults as makers inside and outside of school around the globe (Dougherty, 2013; Peppler, Halverson, & Kafai, 2016a, 2016b). Much research has focused on developing and researching the affordances of construction kits and tools that facilitate the making of digital, tangible, or hybrid artifacts (Blikstein, 2015; Resnick & Silverman, 2005), which vary from personal robots and drones to online games and animated movies. It is only recently that the maker movement has expanded into the fields of bioengineering and synthetic biology, in which people engineer bacteria and use them as tools for designing applications by generating novel outcomes that are not normally found in nature, varying from lab-grown leather (Modern Meadow) to mushroom-based building bricks (Ecovative).

Making with biology, however, is quite distinct from making with electronics or craft materials in several ways. First, biological processes are irreversible and do not involve reconfigurable and replaceable solid parts. Biology outcomes are not immediately apparent or visible because it often takes hours or days for growth. Likewise, biomaking is not as customizable or personalizable as electronic and craft making because of lack of ready-to-use construction kits on the market. Finally, most biologically designed materials cannot be used directly by makers because of government regulations. These particular constraints therefore challenge many of the insights that have been gained in previous research on educational making, which considers the quality of hands-on activities—in particular tinkerability—as key to generating interest and motivating learning (e.g., Blikstein, 2013; Martinez & Stager, 2013). This difference is further highlighted by the centrality of assembly, or step-by-step, practices within biomaking. Within the maker movement, tinkering is often foregrounded above assembly, since it seemingly goes against constructionist learning by requiring rote repetition rather than experimentation (Resnick & Rosenbaum, 2013). For many forms of making, however, it is important to master the craft and skill required for assembly before participating in productive tinkering. With this in mind, we therefore consider how assembly and tinkering are equally important in considering the depth of making at large.

In this paper, we present our educational efforts in biomaking, paying attention to opportunities and challenges for assembly and tinkering. Within our classroom-based workshops, students manipulated single-cell organisms (bacteria) to produce a desired product such as color pigments or fluorescence and then developed applications for these products, including a bacteria-painted logo (biologo) or a glowing water sensor (biosensor). We analyzed our classroom observations and focus groups interviews in order to address the following questions. In what ways could assembly-focused practices be considered a maker activity? What role does assembly play in helping novices learn skills and an understanding of materiality? In the discussion, we consider how the answers to these questions help to expand current definitions of making with an eye to how both tinkering and assembly approaches can create opportunities for greater learning and growth.

Background

Tinkering is often considered one of the central features of educational making and describes how people mess around with different materials for the purposes of experimentation and play (Honey & Kanter, 2013; Resnick & Rosenbaum, 2013). Rather than proceeding from a top-down set of instructions, construction here is built upon bottom-up modifications that unfold over time. Here, makers learn through the process of “bricolage” (Turkle & Papert, 1992), or ongoing negotiations with materials and contexts, rather than rote, logical procedures and practices. In order for one to tinker, a few factors are usually required. First, one needs to have modular elements that can easily be moved around and changed in order to produce new outcomes (Resnick & Silverman, 2005). Second, the feedback of these changes must be discernible in some way, whether through sight, sound, or otherwise (Resnick & Rosenbaum, 2013). And finally, tinkering requires enough knowledge to guess how changes to elements in an artifact may affect the outcomes. One might not know the exact outcomes but one should have or work to develop a sense of what might happen through these modifications. Thus, a project made through tinkering requires sophisticated knowledge and understanding of the processes.

While tinkering is often touted as the gold standard of making, we argue that the act of assembly—or engagement with predetermined step-by-step processes—is just as important. Far from unusual, this approach can be seen in a range of related maker contexts, whether in craft practices such as carpentry and sewing, or skilled trade work such as plumbing and welding (Rose, 2004). Here, the act of becoming more skilled over time often requires following existing routines and procedures in order to become more familiar with tools, materials, and practices—for example, following a sewing pattern to tailor a shirt or using a checklist to diagnose a plumbing issue. Only through repeated practice can one acquire this database of “tactile knowledge” that allows one to eventually become an expert within a field. Indeed, this assembly approach might be seen as the foundation of apprenticeships, in which beginners are coached through a series of highly delineated activities—modeled and scaffolded by some authority—along the way toward becoming a competent creator (Collins, Brown, & Newman, 1988; Lave 1988).

Likewise, assembly is often an essential entry point in the maker movement, since it is how people can gain the basic skills or knowledge they need in order to later create things of their volition. This can be seen within most commercial maker kits—for example, an air-rocket construction kit or a *Star Wars* Lego kit that contains clearly defined directions. Consider the creation of a circuit diagram when making a robot; there are predetermined rules for how components need to connect to yield a desired result. Similarly, in using maker tools such as a 3D printer or a laser cutter, there are diverse projects one can create with these objects, but there are still particular rules and protocols governing how these are appropriately used. Following directions therefore allows one with little to no skill or knowledge to jump into producing an artifact. While some have argued that such assembly can become a rote practice that does not support rich cognitive engagement (Blikstein, 2013; Espinoza, 2011), we consider how assembly approaches still lead to rich experiences that support becoming an efficient maker.

Methods

We implemented two consecutive biomaking workshops to high school students in two STEM-elective courses in a public charter school in a Northeastern city in the United States. Participants were 16 juniors and 18 seniors, among whom 55% of students self-identified as White, 24% Black, 9% other, 6% Latino/a, and 6% Asian. In terms of gender, 76% of students self-identified as female and 24% as male. The participating teacher at the charter school (a trained biologist) and two lab technicians led the workshops. Students were arranged in groups with two to five students. Both groups (juniors and sensors) participated in both workshops.

Our research team (including researchers, biologists, and designers) worked with the classroom teacher to develop the two biomaker workshops. Each workshop focused on the creation of a different product (see Figure 1). In the first workshop (biologo), students first designed a team logo and then created three different forms of the logo using bacteria-created pigments. These included a 3D logo where the pigment was encapsulated into shapes using sodium alginate, and two 2D logos painted on petri dishes using two different techniques (one using filter paper as a base, and one without). In the second workshop (biosensor), students learned about different environmental water detectors, and then re-created a version of these detectors using bacteria that glowed in response to arabinose (sugar) in water. Both workshops included a fabrication phase and an application phase. In the fabrication phase, students engaged with the process of bacterial transformation. This involved inserting foreign DNA into *E. coli* cells to produce a desired substance, whether colored pigment or glowing proteins. In the application phase, students used these substances to create final artifacts, whether the logo forms or the water sensor. Within both phases, students followed predesigned procedures, which were developed by our team. The biologo workshop lasted for four days, while the biosensor workshop lasted 8–10 days.

In order to answer our research questions regarding assembly and tinkering, we looked at the design and implementation of the biomaking workshops, as well as student reflections on these activities. For each day of the workshops, we videotaped instruction and activity sessions, wrote class observations (field notes), and photo documented artifacts. After both workshops, we held four separate focus groups (about 20 minutes each) with randomly chosen students (3–4 per group). Here, we asked students to reflect on their experiences creating the sensors and logos. Looking across the data, we identified where students had opportunities to engage with *assembling*—engagement with step-by-step directions in service of creating a final artifact, and *tinkering*—iterative, experimental engagements with physical materials and tools. We looked at where and why these opportunities arose (or did not), as well as student reflections and perceptions of these activities. We highlight some themes of the analysis below.

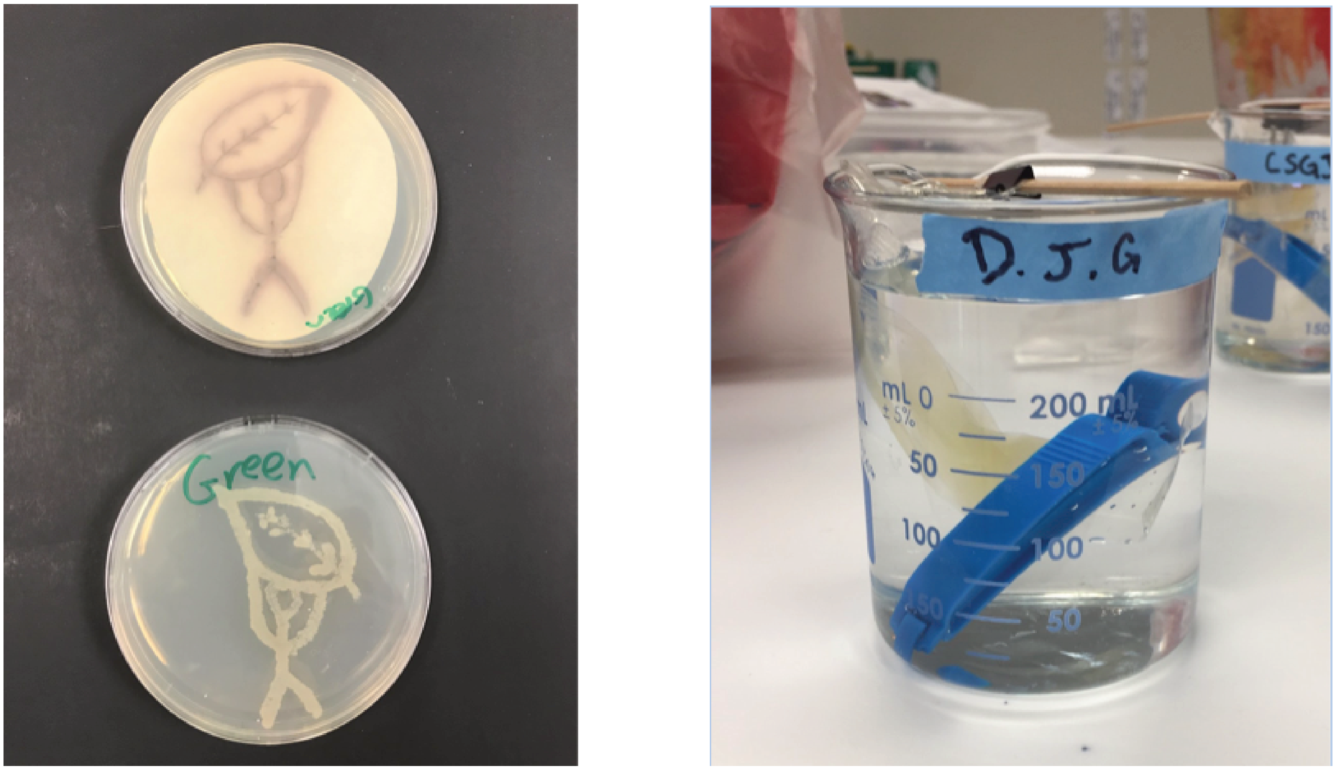

Figure 1. (Left) different painted logo forms using bacteria pigments for the biologo activity; (right) water sensor using arabinose-detecting bacteria that glowed for the biosensor activity.

Findings

Assembly in Biomaking

In our workshops, students had many opportunities to engage with biomaking assembly. One reason for this was the inherent nature of biomaking. First, dealing with living materials necessitates specialized procedures and environmental conditions (e.g., adding the appropriate level of nutrients and maintaining an ideal temperature for growth), and second, biological processes often require a long amount of time to see results (e.g., waiting 24 hours for bacteria to reproduce and deliver the desired substance). For this reason, it is often easier for biomakers to follow predetermined steps for known processes rather than allowing them to tinker from the start. For the fabrication phase of the workshop, students were engaged with known procedures of genetic transformation of bacteria that included: heat shocking and cooling the bacteria to open and close their pores for the new DNA to enter the cell, providing nutrients to the bacteria, and letting them incubate at a steady temperature for many hours to allow for growth and replication. In order to facilitate in-class results, our research team developed a lab protocol for students to follow. Steps were highly specific; for instance: “Incubate cuvette in warm water bath at 42ºC for 90 sec” and “Fit and twist syringe tip into cap and aspirate contents of cuvette. Keep pulling plunger until ~6mL line.” Interestingly, while our team had to tinker with lab procedures beforehand to develop this checklist, students were expected to follow these directions exactly in order to produce the desired result.

Despite the fact that students were not given freedom to play around with the material, they still gained a high amount of knowledge through this process. First, students acquired some amount of tactile ability with the different lab tools and materials, whether using a syringe to move liquids from place to place or the appropriate method of using a warm-water bath. Mostly, this was accomplished through hands-on engagement with the tools, as well as active guidance and scaffolding from our lab instructors. For example, while delivering the nutrients to their bacteria samples, several groups had trouble adding the prescribed amount of the nutrient Lysogeny "L" broth (1 ml) into the cuvette (a container that held the bacteria). Our instructional team helped with this process by premeasuring the appropriate amount of broth (once they realized that students had difficulty with this) and also giving them tips for how to collaborate with the tools (e.g., "How about one person holds the cuvette and the other uses the syringe [this way]?") (see Figure 2, left) (field notes, 2/6/2017). By the second workshop, we observed that students were more comfortable with the procedures and tools, often moving through the steps independently without much support (field notes, 3/13/2017). This is not a trivial matter considering the important role of physical craft—that is, knowing how to handle or use different laboratory tools and materials efficiently and appropriately—in becoming a competent bench scientist.

Through guided assembly, students also gained a greater understanding of biological processes underlying the given procedure. This was supported through our instructional team, who not only modeled each step to students, but also simultaneously explained the reasoning behind these steps. Because students were going through these preordered actions together, they had opportunities to talk about these processes at greater length. For example, during the step of inserting the L broth, students had several conversations with the instructors about why this was necessary, something that led to jokes about making the bacteria "happy" and "comfortable" by feeding them something like "chicken cutlets" and "hamburgers" (field notes, 2/6/17, 2/7/17). Sometimes this extra conversation was even used as a basis for changing how students engaged with the materials. During the biologo workshop, two groups talked with the instructor about the purpose of the warm-water bath, which allowed "pores" of the bacteria to open up to allow for the intake of the new DNA. After hearing this, one team member noticed that her cuvette was not fully submerged and modified how it was sitting within the flotation device so that all of the bacteria would be appropriately warmed (field notes, 2/6/2017). Throughout the workshop and in focus groups, students referred back to this idea of feeding the bacteria and opening its pores, therefore illustrating how their ongoing conversation reinforced the concepts behind the process. From this perspective, students' engagement with assembly practice was a useful scaffold in helping them to become effective at biomaking, which relies heavily upon understanding and implementing prescribed procedures of biological lab work. Through gaining tactile knowledge of how to use tools and equipment in tandem with knowledge about why and when to use these techniques, the students were therefore on the road to become more efficient and effective biomakers.

Figure 2. (Left) two students collaborate on how to use a cuvette and syringe after being given guidance from the instructor; (middle) figuring out where to clip the dialysis bag to suspend the bacteria in the "mystery" solution; (right) painting logo with bacteria on filter paper (right).

Tinkering in Biomaking

Though students did not have opportunities to tinker in the fabrication phase, they had slightly more freedom to play with materials during the application phase. In this phase, students built artifacts using the products they grew out of their genetic transformations. In the biosensor workshop, students were given dialysis tubing, wooden sticks, plastic clamps, and binder clips to build a water detector that would glow in the presence of arabinose in a "mystery" beaker of water (see Figure 1, right). While students were given a list of directions for building this device, their physical interactions with these materials were less determined than in the fabrication phase. Again, this was supported through instruction. After being given the dialysis bags, groups were asked to clip them to create a little container to hold for the transformed bacteria. Different groups chose to clip their bags in different spots (e.g., toward the bottom, toward the middle). When they asked about which method was best, our instructor replied: "I guess we'll see," thus trying to make clear the experimental nature of the process. When they continued to ask for clarification about other steps, the instructor did not direct them on what to do, but instead explained what the purpose of the step was such that students could make their own decisions. For instance, after clipping her bag, one student asked how she should attach this device to the stick when suspending it in water (see Figure 2, middle). The instructor explained that it was important for the bacteria to be entirely submerged in the water to react to the arabinose. Based on this comment, the student worked on her own to calibrate the right height of the bag such that it would be appropriately covered and so she could see it clearly during the next phase of the project (field notes, 3/15/17).

Within the biologo workshop, there was even more variation on how students dealt with materials. Partially, this was due to the fact that students were purposefully asked to work on three versions of their logos using different techniques. Two of these logos were flat designs that involved "painting" with bacteria on petri dishes either directly onto nutrient agar or on filter paper placed on top. The third logo was three-dimensional. This required encapsulating the transformed bacteria into sodium alginate shapes (a gelatinous substance often used in cooking), which were then kept in place using hot glue gun outlines. Unlike the fabrication phase, in which steps were highly delineated, how students dealt with these materials differed according to preference. For instance, when trying to figure out how to "paint" on the filter paper, different groups used different techniques, including: (a) attempting to "free" draw their logo onto the filter paper without any physical guides, (b) tracing the logo off their predrawn designs by placing them underneath the petri dish, and (c) drawing in pencil on the filter paper and redrawing this image with the bacteria (see Figure 2, right; field notes, 2/2/2017). Other moments of tinkering that occurred involved figuring out the actual tools for painting (using a Q-tip or an inoculation loop), and how to create the most effective hot glue gun outlines for the 3D logo. While some students used the hot glue gun to trace around each drawn line of their logos, others completely redesigned their images in order to make them into solid silhouettes that were easier to outline (field notes, 2/8/2017).

Despite the fact that students were experimenting with different ways of interacting with the materials during the application phase, it is arguable whether this activity could count as a legitimate form of tinkering. In tinkering, one important element to consider is how students iteratively engage with the materials based on feedback they receive as part of the process (Resnick & Rosenbaum, 2013). Here, the lack of immediate feedback from the process (because of the time required to actually see an outcome) makes it unclear how intentional students' modifications were. As one student noted: "I think the tracing over the bacteria at least for my part was kind of difficult, because it didn't really feel like I was doing anything when I did it" (Dino).[1] Because it would take another 48 hours of growth before there would be a large enough concentration of bacteria to be able to see the color, students could not see how well their individual tinkering influenced the final outcome. This was true about all the other modifications that students made; where they clipped their dialysis bags or whether or not they used pencil on filter paper was usually less a matter of trying to shape their projects' outcomes than what was easier or more comfortable to them at the time.

Reflections on Assembly and Tinkering in Biomaking

In the focus groups, students reflected about their experience with assembly and tinkering. About the entire process, students reinforced that they had primarily engaged with the assembly making. About making the biologos, James stated, "There were directions and we followed them," with Yoana and Giovanni, respectively, describing these processes as "straightforward" and "just … follow[ing] the rules." In general, students liked having these directions available to them, stating that that made the process more accessible, especially considering that this was an unfamiliar context and their "first time actually experiencing something like this" (Laila). About the benefits of having directions, Caroline further added: "The thing we did … on the second day where we heat the bacteria and then we froze them. It was pretty cool just because it was easy and I understood it."

Laila further explained that it is difficult to tinker in an unfamiliar context: "I follow [directions] very well but I can't adapt myself with [the] little bit [we experienced of] such stuff." As Yoana stated, this difficulty of tinkering was further pushed by not knowing what the outcome of these projects was supposed to be: "We didn't really—we knew what the color should have turned out [to be], but we didn't know how much of it would grow, like exactly what to expect." Thus, one big reason having directions was helpful was in getting actual results, that is, actual color or a glowing biosensor. This is true especially considering the limited time in the classroom, as well as students' limited knowledge and prior experience with these processes. Giovanni, for instance, describes the moment of having a working result: "It worked … and I was like, I was really excited and wow, it's really interesting."

This does not mean, however, that students did not want more opportunities to tinker. Though we outlined steps for students to follow in order to produce successful results, a number of the projects within both workshops did not turn out as expected because of the unpredictability of living organisms

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1. This and all following names are pseudonyms to protect confidentiality of participating students.

and growth processes. For instance, several of the different pigments that students created could not clearly be identified as the intended color (e.g., green, purple), and instead were nearly clear and/or nearly black. About this, Caroline stated:

> Well, I did the one where we had to build the wall with the hot glue and the agarose in it. So my plate didn't turn out the way I expected to. It's not green, I can't really see the design, and it's sad—it's disappointing to see it. But, I'm interested in finding out what I did wrong and why what happened happened and how I can fix it.

Similarly, Giovanni stated: "Two of [our logos] didn't work. So, that's our challenge I guess now to see how it would work and to fix them," whereas Yoana suggested adding more time to the workshop to aid in tinkering. From this perspective, the desire to tinker comes after gaining some basic knowledge and experience acquired through the assembly process. Even though biomaking does not naturally lend itself to tinkering in the same way that other more "typical" maker activities do (e.g., electronics, programming), there is still a need to incorporate tinkering into the activity as a way of engaging students authentically.

Discussion

Our findings illustrate how biomaking can be considered a form of making but one that includes more assembly than tinkering practices. While tinkering is essential in developing greater expertise and understanding of a field, assembly is often a key first step in acquiring this ability over time within more traditional crafts or trades (Rose, 2004; Lave, 1988). With biomaking, the affordances of assembly as an entry point become even more prominent since producing viable outcomes in and of themselves requires some basic knowledge, time, and experience. Here, engagement with step-by-step processes can help students feel comfortable and successful within the unfamiliar context of biomaking—something demonstrated through our student reflections. Thus, while tinkering may work better at introducing novices to more familiar context such as electronics, gaming, or crafting, assembly might be a more ideal starting point for novel or new contexts such as biomaking.

That said, our findings also point toward the importance of increasing opportunities for tinkering. Following Resnick and Rosenbaum (2013), some important aspects of tinkerability are modularity of elements, as well as how easily people can receive feedback from their changes—factors that are less present in biomaking. One potential way of addressing this difficulty is to allow for simultaneous tinkering; in other words, have students create multiple iterations of a project at once and wait to see the outcomes for each of these iterations at the same time. In some respects, this is what we attempted to do with the biologo workshop in which students created three forms of their logo. In another version of this activity, it might be useful to be more explicit about how these multiple forms can be connected to tinkering. Another potential solution would be to focus more on tinkering in the application rather than fabrication phase. The latter—which includes genetic transformation—is a more rigid process and requires a greater depth of background and experience to modify. The application phase—when students actually construct artifacts using the biologically fabricated products—falls in line with more typical maker practices and therefore lends itself to greater amounts of in-the-moment modification. Adding tinkering here would involve giving students more opportunities to experiment in building their final artifacts. In the biosensor workshop, this might mean abandoning parts of the predetermined procedure (i.e., clamping the dialysis bag to the wooden stick using the binder clip In the prescribed manner) and instead providing a range of possible materials that students could use to create their own custom contraptions for suspending their transformed bacteria in arabinose water. Rather than abandoning opportunities for tinkering in biomaking altogether, we can therefore create small openings for experimentation *in between* the assembly approaches that are required for novices in this arena.

Our analyses of biomaking experiences and reflections revealed that making comes in many forms, materials, and processes. Only by giving students opportunities to engage with both assembling and tinkering can we begin to advocate for biomaking as a true form of making. However, this goes both ways—rather than privileging tinkering practices at large, researchers should consider how assembly approaches can supplement what students are already doing as makers, even in those areas of computing and crafting that tend to privilege experimentation and play. There, approaches that include mastery and skill through thoughtful and reflective repetition might also supplement the kind of learning that occurs through tinkering. Only by looking at the balance between these two approaches can we truly support young makers in gaining more mastery and expertise across diverse domains of creation.

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