Affordances of Digital, Textile and Living Media for Designing and Learning Biology in K-12 Education

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Abstract: In this symposium we are examining the affordances that particular materials hold for supporting learning biology inside and outside of school along three dimensions: (1) digital materials that encompass screens and software through which students can interact, (2) textile materials that allow students to wear bodysuits that can help them visualize physical movements on interactive displays, and (3) interactive materials that allow students to interact with living microorganisms through games in science museums or through computational models that students design and test against the real data in science classrooms. Panelists will discuss how affordances of tinkerability (messing around), perceptibility (seeing results), expressivity (customizing experiences), and usability (using outcomes) entered into their considerations when designing and studying of environments, games, and design activities for interacting and learning with biology.

Overview

In this symposium we want to turn our attention how affordances of different media—digital, textile, and living—can be leveraged for learning and teaching about biology using participatory simulations, gaming environments, or design activities. The concept of affordances, first introduced by Gibson (1977) emphasizes that objects in the world are not just perceived in terms of their shapes and spatial relationships but also in terms of their possibilities for interacting with them. Later work by Norman (2013) applied the concept to technologies and interactivity. Considerable research has extended affordances into design of educational construction kits and tools to make games, robots, wearables and many other artifacts, on and off the screen (e.g., Blikstein, 2015; Resnick et al., 2008). More recently, the development of synthetic and DIY biology has made many new tools accessible and affordable for non-professional biologists and anyone interested in "hacking and tinkering with biology" (p. 258, Kuznetsov, Taylor, Regan, Villar & Paulos, 2012). However, the affordances of playing and making with biology are quite distinct from those with digital or textile materials and challenge many of the insights that have been gained in previous research, especially those that consider the quality of hands-on activities, processes of making, and the sharable, usable and personally meaningful artifacts key in generating interest and motivating learning (Peppler, Halverson, & Kafai, 2016 a and b):

• **Tinkerability** is characterized as playful, experimental iterative style of engagement in which learners are continually reassessing their goals, exploring new paths and imagining new possibilities—or as having a conversation with the material. In these definitions, tinkering is often seen in opposition to planning (top down instead of bottom up). However, many activities with living cells are distinct from the 'typical' contexts of digital or textile creation since these processes are time-dependent: they require a full run of the entire lab procedures before one can see the expected result. In other words, whereas tinkering in engineering, crafting, and coding contexts can occur because individual processes are discrete—iterating on a gear mechanism or developing a specially defined procedure—in biology they occur in a holistic fashion—fixing a 'mistake' means doing a lab procedure all over again and waiting for the result. Additionally, tinkering with living cells involves liquids rather than the discrete solid parts seen in ‘typical’ electronic making, something that makes the process of tinkering inherently more difficult.

• **Perceptibility** illustrates how designs can yield immediate feedback to users either on the the progress or results of their interactions. For instance, a coder can instantaneous see the result of a bug they fixed in a program whereas in biology this process is slowed down because of the requirements of the living organism. While microorganisms grow quite rapidly, it often takes twelve hours or more for any genetic transformation to yield an outcome. More importantly, due to scale and colorlessness of the microorganisms, makers often cannot see the outcomes of their designs or their changes at first.

• **Expressivity** because processes are not yet as customizable and personalizable as seen within digital or textile making. In many maker activities, the notion that individuals can make personal artifacts or designs that are based on their interests, desires, or needs, is considered one of the driving motivations for student engagement and learning in maker activities. But due to the nascent state of biodesign along with the available tools and processes on the market, this individualization is often not easy to accomplish. Whereas consumer-grade electronics kits have created opportunities for lay people to create personalized computational designs, people with limited biological knowledge and background are not yet as able to produce biodesigns that fulfill their individual goals and purposes. Instead, they must depend on existing protocols and materials developed by experts.

• **Usability** captures the dimension that many designs that can be used by themselves or others for play, learning, or work. In biomaking, usability of created products comes with different affordances and constraints. Because living designs can perish at some point, careful thought must be paid into designing settings that either keep them alive (e.g., enough nutrients, correct temperature) or develop everyday applications that fully make use of their products (e.g., transferring color into textiles). From this perspective, typical making affords numerous ready-made situations for usability (e.g., kits, everyday applications), while biomaking has not yet reached this point of development in its short history.

This symposium brings together researchers from the learning sciences, human-computer-interaction, and computer sciences, and science education to discuss how these affordances featured into their design and research of learning and teaching biology within K-12 education inside and outside of school. The first group of studies has focused on tangibility by using textile materials in new ways to introduce students of elementary and middle school ages to interacting and understanding complex systems. In BeeSim, Joshua Danish and colleagues will present their efforts of designing bee costumes and flower environments that let second grade students emulate the behavior of honey foraging bees. In BodyViz Tammy Clegg and colleagues provide an illustration by designing bodywear that can be worn by students as they exercise to visualize on the body as well as on the screen their movements and collect data. The second group of papers uses living materials on the microscopic level to engage students in interacting and designing. In the work by Paulo Blikstein and colleagues they design museum exhibits in which visitors can play games with living cells by leveraging their light sensitivity while the paper by Justice Walker and colleagues from the University of Pennsylvania, high school students adopt a design approach to biology and learn how to hack microbes in order to create their own biosensors that react to environmental contaminants.

Each of the research designs illustrates how the affordances of particular materials—digital, textile or living—can be leveraged to augment learners’ experiences in unexpected ways. To launch the discussion with the learning science community, each presenter will give a 12-minute overview of how they approached the design of their materials and activities in terms of addressing particular affordances, and then present outcomes from learning research. Our discussant, Michael Horn from Northwestern University, will review overarching themes and then open up the panel to Q&A with the audience.

Modeling bees by acting as bees in a mixed reality simulation

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Advances in mixed-reality and augmented-reality technologies, which allow students to engage with computer models and simulations using their bodies, have great potential for supporting cognition and learning (Lindgren and Johnson-Glenberg, 2013). Research in this area has been particularly focused on the value of embodied cognition, recognizing how moving one’s body can provide unique insights into complex phenomena, particularly when coupled with computer simulations that help students to make sense of their movements. However, much of the work in mixed reality learning environments has focused on non-biological concepts such as physics and chemistry, and frequently focuses on individual learners or dyads. In contrast, the Science through Technology Enhanced Play (STEP) project has explored how larger groups of students (ranging from 4-12 at this time) afford unique opportunities for engaging with complex science phenomena in early elementary classrooms Danish et al., 2015). We report on a recent implementation of the *STEP: Bees* software and curriculum where students take on the roles of honeybees to understand how bees collect nectar, and how this supports the growth of the hive, as well as leading to pollination in the local flower population.

In designing and refining the STEP environment, we have developed a sociocultural framework for embodied cognition (Danish et al., 2017) which aims to couple prior efforts at understanding the role of the body in learning with attention to how the interactions between participants and their peers, teachers, and technology all play a unique role in supporting cognition and learning. In the S*TEP: Bees e*nvironment, students engage in a number of participatory simulations (Colella, 2000) where they take on the role of honeybees foraging for nectar. To do this, they physically play the role of honeybees moving around within their classroom (figure 1, right). The STEP software uses Microsoft Kinect cameras to track their motion and feed their movement into a computer simulation which is projected at the front of the room (figure 1, left). Thus as students take on the roles of bees, they see bee avatars moving within the computer simulation, responding to their motions. As a result, students receive information and feedback from both their peers and the computer simulation as they embody the roles of honeybees.

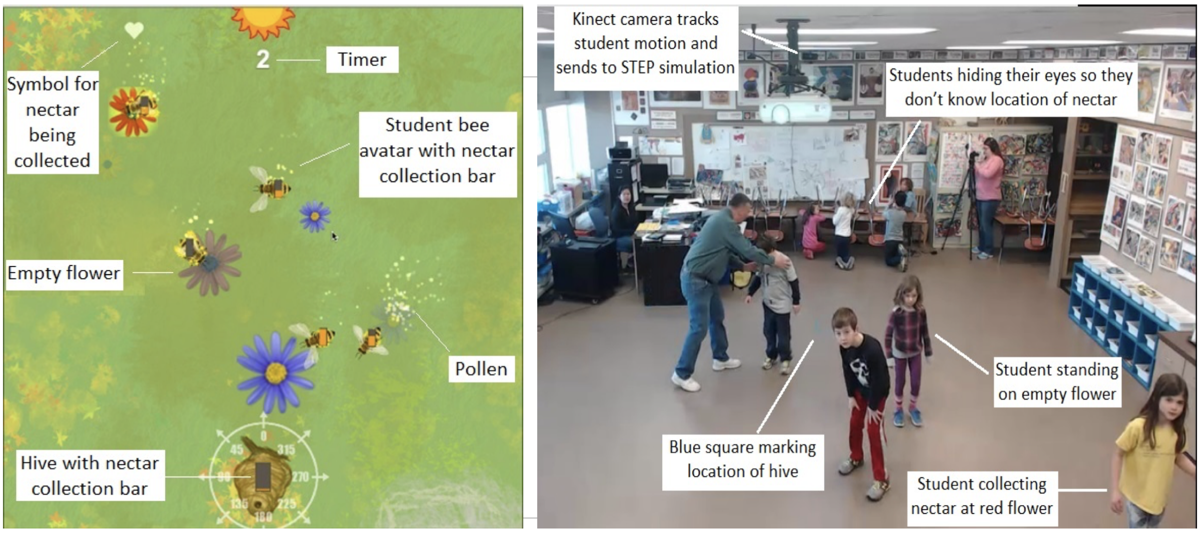

Figure 1. The *STEP: Bees* Environment. The computer projection (left) depicts honeybee avatars interacting with a simulated environment while the students move around within the classroom (right).

To describe the unique affordances of the biological subject matter in this design, we present and contrast new analyses from two prior studies. First, we report on an implementation where 16 children ages 7-8 participated in the *STEP: Bees* curriculum with two teachers at a public elementary school in a small city in the midwestern United States. Previous analyses of the *STEP: Bees* Environment (Danish et al., 2017) focused on the role of embodiment in their learning. The present study focused instead on the unique affordances of the biological context, and of the role of our design for supporting learning within a biological context. To this end, pre-post interviews and drawings were used to measure changes in students conceptual understanding as a result of the intervention, and video analysis was used to document the process through which students learned the content. Video analysis will demonstrate the unique affordances of small group, embodied mixed reality simulations for helping students engage with this complex biological phenomena. In particular, we will show how the body provides unique opportunities for *tinkerability*, while also supplementing the affordances of the computer simulation for enhanced *perceptability*. Using one's body also provides unique opportunities for both *usability* and *expressivity*. In particular, we have found that students move their bodies quite spontaneously, and often express their understanding both in ways that are interpreted in unique ways by the simulation (e.g., their movement in space moves their avatar) and by their peers (e.g., gesture, running, and jumping to convey ideas). Finally, we will provide a contrast with our *STEP: Particles* environment (Danish et al., 2015) to discuss how explorations within this biological context led to new affordances and constraints that differ from the previous physics context. In particular, students' ability to take on a first-person anthropomorphized perspective appears to have led to unique forms of engagement with the content. This will allow us to discuss the unique affordances of both using one's body to study complex science, and using one's body to study biological concepts where there is a one-to-one mapping between one's body and an agent in the system being studied, as well as differentiating between the role of biological contexts of study on student learning in this kind of mixed reality environment.

Real-time play in microscopic worlds

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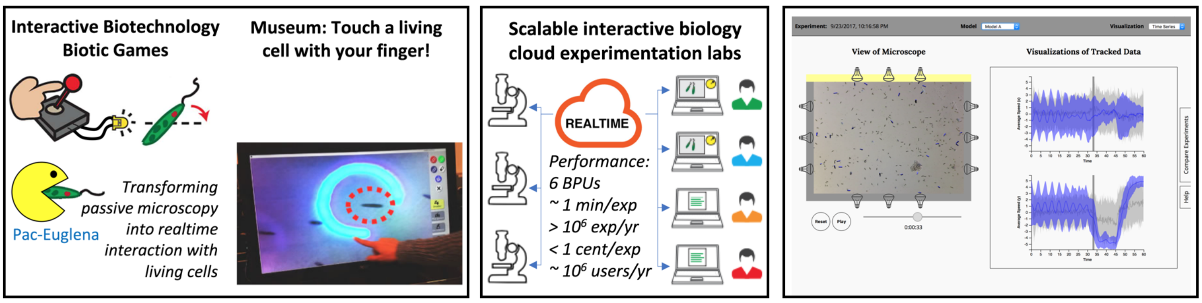
The microscopic world of biology is full of wonders to be explored, and that informs our understanding of life at all scales. Children in schools predominantly access this world through static observational microscopy. Observational microscopes open a window into that world, with limited possibilities to manipulate it. Other media such as robotics construction kits, programming languages for children, and videogames have demonstrated the educational potential of interactivity (Kim et al., 2016); and academia and industry have been developed ways to interact with microscopic worlds for decades. Our interdisciplinary research groups have explored two ways of bringing interactivity into biology: real-time interactivity through technology that is in the same physical space as the user, or remote interactivity through cloud-based systems (see Figure 2). An essential principle to developing this form of interactivity is to digitize the biological signal, e.g. with computer vision algorithms that track microbiological organisms and processes, and augment and enhance it for use in a variety of ways (see "Data augmentation," Blikstein, 2014).

Real-time interactivity lends itself particularly well to ways of *playing with* the microscopic world. The Riedel-Kruse Lab built two systems that exploit intuitive notions of interactivity through tactile experiences (i.e. *Human-Biology Interaction*; Lee et al., 2015): Trap it! (Lee et al., 2015) and LudusScope (Kim et al., 2016). These systems use touch screens, microscopes and augmentation - either through projections or through mobile devices, to create *biotic games*, i.e. games that operate on the biological processes and allow children to interact with these processes to play games like virtual soccer or maze-based games (Riedel-Kruse et al., 2011). The core biological process in both systems is the phototactic behavior of Euglena, i.e. the real-time reaction to light in form of changes to movement direction. In Trap it!, users can interact with living cells by drawing patterns on a touchscreen displaying the microscope view of the cells. These drawings are projected onto the microscopy field as light patterns, prompting observable movement in phototactic responses. In LudusScope, a smartphone microscopy platform, users can interact with individual Euglena cells by digitally selecting them via the phone touch screen, and then influencing their swimming direction via a joystick that controls four directional LEDs arranged around the microscope. Both systems have been used in various informal contexts such as museums. In the user studies, the fact that the interaction involved real and not simulated organisms was particularly intriguing for children, and researchers observed intuitive and playful interactions with the system (Kim et al., 2016; Lee et al., 2015).



<u>Figure 2</u>**.** Left: Real-time interactivity in same physical space: LudusScope and Trap It!. Middle: Remote interactivity with microscopes. Right: Lab in the Cloud, model and real data in same representational spaces

Beyond just *playing with*, interactivity is also powerful for *learning about* biological phenomena through authentic inquiry, enabled by remote laboratories. Remote laboratories consist of physical laboratory equipment, e.g. microscopes or other tools, that is accessible over the internet: But these *interactive cloud labs* (Hossain et al., 2017) enable multiple users at the same time to execute real biology experiments, in real-time or asynchronously, and to get that data for further analysis. Our labs developed and used two remote laboratories: the physarum lab for remote asynchronous experiments on a slime mold (Hossain et al., 2015); and an interactive cloud lab for both real-time and asynchronous experiments on Euglena (Hossain et al., 2016). These systems remove crucial access barriers for schools, such as safety concerns, maintenance costs, and logistical requirement, that have impeded inquiry-based approaches in biology classrooms. Furthermore, they are versatile and flexible: by centralizing the core technology, and digitizing the data, they can be implemented in large online courses (Hossain et al., 2017), or in classrooms (Bumbacher et al., 2016).

By embedding these core technologies in web applications, we can create systems that enable rich ways of doing inquiry not possible otherwise - instead of having to combine *different* systems for modeling and for experimentation, we can integrate affordances for modeling and experimentation into one system. This is in line with the bifocal modeling framework that brings simulated and real-world data into the same representational space for simultaneous, real-time comparison (Blikstein, 2014).

Using the Bifocal Modeling framework, we developed a *Lab in the Cloud* that includes the biological data from the remote lab into a simulation environment; a classroom study using an earlier version of this web-application showed that students productively engaged in science inquiry (Bumbacher et al., 2016). We are currently developing and testing the next iteration of this technology (see Figure 2 right) that has increased experimentation, modeling and data representation capabilities. A major focus of this technology is to enable students to seamlessly create explicit comparisons between multiple experiments, experiments and models, and multiple models. We hope that this work will contribute to a theory-driven design framework for technologies designed to engage students in the relevant discursive and reasoning processes of science inquiry that integrate practices of modeling, experimentation and argumentation.

Physiological investigations with live physiological sensing and visualization tools

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Wearable sensing technologies enable new forms of scientific inquiry experiences that enhance learners personal connections to inquiry processes (e.g., asking questions, planning investigations, collecting data, making claims) (Chinn & Malhotra, 2002; Bower & Sturman, 2015). Fitness trackers that learners wear on their wrists, for example, allow children to capture data about their everyday activities (e.g., steps taken) and vitals (e.g., heart rate) that can be analyzed later on mobile or desktop devices (e.g., Lee & Dumont, 2010). In this paper, we present the BodyVis project in which we take a textile and digital approach for helping elementary-age learners understand living data generated from their own physiological functioning (see figures 3a and b). Unlike other wearable approaches, we leverage the affordance of *perceptibility* to provide real-time model-based and analytic visualizations of learners *physiological* functioning.

We have developed a set of Live Physiological Sensing and Visualization (LPSV) tools that leverage the body as a platform for inquiry (Clegg et al., 2017). LPSV tools sense and visualize learners' physiological functioning (e.g., heart rate, breathing rate) in real time. BodyVis (Norooz et al., 2015), senses and visualizes a wearers' heart rate and breathing rate in real-time on an e-textile shirt that displays a model-based representation of learners' upper respiratory organs (Figure 3-left). SharedPhys (Kang et al., 2016) allows up to six wearers to project their heart rate in real time on a large-screen display (Figure 3, right).

We implemented these tools in two iterations of a four-session activity sequence in three elementary school classrooms that progress from expiration of the LPSV tools and developing questions, to semi-structured inquiry activities, and finally planning and implementing learners' own choice-based investigations. Our analysis of this sequence of activities in a first, second, and fourth grade classroom first in 2016 and then in 2017 includes video data of learners' choice-based investigations, interviews with teachers, focus groups with learners, and participatory design with teachers between iterations. We draw themes from an Activity Theory analysis of the LPSV classroom ecosystem in 2016 and a case study of learners' investigations in 2016 and 2017 to understand ways the affordances of LPSV tools influenced children's scientific inquiry experiences.

Figure 3. BodyVis (left) and SharedPhys (right) are two LPSV tools that visualize wearers' live body-data on an electronic textile (e-textile) shirt and a large-screen display respectively.

Co-designing the BodyVis and SharedPhys tools and activities with children revealed that children wanted more and more opportunities to play and tinker with the BodyVis shirt. Each iteration of BodyVis has thus provided increasing *tinkerability* (e.g., ability to remove and replace organs). Learner surveys, focus groups and video observations show that the *perceptibility* of LPSV tools' live visualization was deemed motivating and enjoyable by learners. However, learners need opportunities to pause visualizations and to observe the tools being used by others to promote analysis and reflection on results. We found that with additional scaffolds, even early elementary learners leveraged affordances for *expressivity* to create novel, personally relevant questions. However, more support is needed for fostering creativity for investigation questions more systematically among elementary learners of all grades. Finally, our study identified some *usability* issues that must be considered for broader use of LPSV tools in the classroom (e.g., rules and norms around touching and sensitive topics that may arise from live personal health data).

Growing and designing biosensors in high school classrooms

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The Maker Movement has had an increased presence in educational settings as researchers have demonstrated how these hands-on activities can exist in traditional disciplinary areas (Halverson & Sheridan, 2014). While making has become popular within computing and engineering (Berland, 2016; Martin, 2015), it has been less emphasized within life sciences. This is partly because maker activities typically involve materials that can be handled and repurposed in flexible ways. Life sciences, on the other hand, often involves living organisms or compounds that must be handled in particular ways, which are predefined and rote. Here, we argue that design thinking may be a useful frame within which to investigate how life science activities could exist within maker contexts. As defined here, design thinking can be understood as the way that people integrate useful knowledge from different disciplines with the goal of creating an artifact that addresses concrete needs (Buchanan, 1992). One promising context for highlighting design in biology is the rapidly growing field of synthetic biology, which looks at how living organisms can be manipulated to serve societal purposes and desires (Kuznetsov et al., 2012). In this study, we highlight an approach toward teaching biology which is situated within design thinking, something we call biomaking.

We report on a biomaking workshop, called bioSensor, that we designed and implemented with high school students within a STEM elective classroom. We investigate the extent to which students engage in design thinking and practices throughout the workshop, which was divided into two phases. In the lab phase, students genetically modified bacterial cells to make them fluoresce in the presence of a sugar called arabinose. Following, students assembled pre-designed devices using common lab materials like petri dishes, clamps, and dialysis tubing such that the microbes could be used detect arabinose concentration within a 'mystery' solution (see Figure 4a-d). In the imagination phase, we asked students to think beyond their tangible artifact toward a hypothetical application of synthetic biology to a real world issue. Groups were assigned different sites across the United States that face well-known environmental contamination issues (e.g., petroleum in the Gulf of Mexico; phosphorous in Lake Erie). We then asked students to design imaginary biosensors to detect pollutants in their assigned environments, which they presented to the class using a design storyboard. This imagination phase was intended to promote student design thinking where lab activity constraints and materials were limited due to the nascent state of the field.

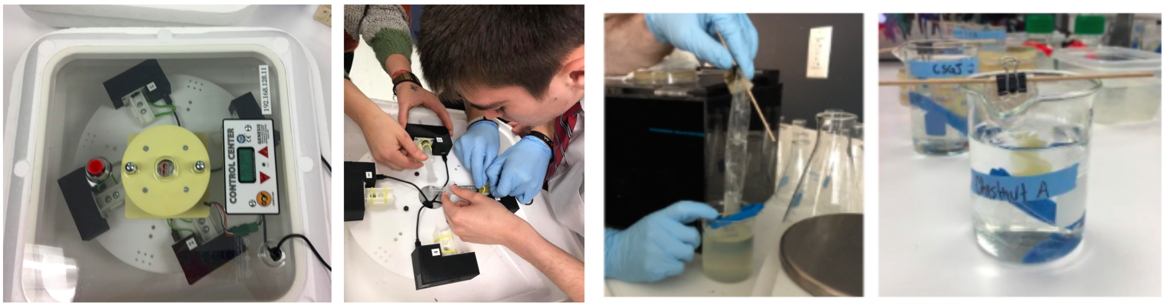

Figure 4. BioSensor construction using bacteria detector (from left to right):
(a) Prototype of portable biomakerlab machine; (b) Students inserting the syringes into the machine; (c) Students inputting the transformed bacteria into the dialysis bag; and (d) completed sensor contraption.

We report on the extent to which students engaged in design thinking in the bioSensor workshop. We analyze how each activity allowed students to: (1) *tinker* with ideas and materials, (2) *perceive* outcomes, (3) *express* themselves and (4) produce *usable* final products. Within the lab phase of the workshop, students' ability to perceive the outcome of their activity was relatively high—that is, they were able to see if their plates glowed or not thus indicating a high or low arabinose concentration. Furthermore, the usability of their product was arguably high within the context of the class since it fulfilled a definite function (i.e., to test for the presence of the sugar). However, opportunities for tinkering and personal expression were severely limited within this phase due to the inherent constraints of wet lab activities in terms of how quickly microbes can respond to genetic or design changes and the general irreversibility of these kinds of processes. The imagination phase, on the other hand, provided different affordances for students. While groups were pre-assigned to environmental sites, they each proposed diverse biodesign solutions, which were developed through several rounds of critique from other students and the teacher. For instance, projects ranged from genetically modified seaweed that would change color to indicate high petroleum concentration in the Gulf of Mexico to mechanical-biological hybrid buoys that would light up in response to high toxic algae levels in Lake Erie. In this way, students were provided extended opportunities to tinker with their ideas and express themselves creatively—affordances not seen within the lab phase of the workshop. From this perspective, the imagination phase addresses the gap between the available resources and opportunities within synthetic biology and students' interest in actualizing personal designs. As biomaking progresses further as a viable classroom activity, there is a need to develop ongoing supports and scaffolds that allow students to simultaneous engage with hands-on wetlab activities in synthetic biology and to develop their design thinking sensibilities within this burgeoning field. In this way biomaking can reach its potential in engaging students as a true maker activity.

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