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Foreword

Little did we imagine, back in early 2019, when we issued the call for submissions for the conference, how prescient our words would turn out to be. Back then we wrote that "*We certainly are "living in interesting times". Times which require all of us working in education to do everything we possibly can to provide everyone with the best possible education to help them navigate and construct the "brave new world" in which they will live."*

The brave new world to which we referred was one in which information technology - in all its manifestations, AI, robotics, IoT etc. - would be a significant driver in changing how we lived, worked and educated young people. The call for papers sought contributions from our community of practitioner-researchers as to how Constructionism could contribute more fully to teaching & learning in this time of change.

The advent of the Covid-19 pandemic has of course changed the landscape in a radical way. As we write the pandemic is an unfolding tragedy, varying only in degree, across all parts of the world and of course the face-to-face gathering in Dublin had to be cancelled. Nevertheless the conference participants were adamant that a proceedings be produced.

This volume includes 44 full papers and each of the keynote speakers also produced a paper elaborating on the themes they would have covered in their talks. There is a strong element of practitioner-researcher in the community and this is reflected in abstracts for panels, demonstrations, workshops and posters which feature in this volume. However these abstracts cannot really do justice to the rich diversity of learning experiences they describe or substitute for the hands-on experiences that would have occurred.

The call for submissions sought to extend the Constructionist dialogue beyond its traditional base of STEM (and coding in particular) and, while the number of such submissions in the proceedings is modest it does include submissions on art, music, drama, social science, civics and geography. But it is the element of dialogue which suffered most from the conference gathering not taking place. We are sure that if the conference had gone ahead the keynote presentations, and the conference chairs, would have provoked a "lively conversation" on how the community sees itself and that at least some of the major research challenges facing the field would have been debated, thus helping to shape the research direction of Constructionism going forward.

The Covid-19 pandemic has brought about change at a rate we could not have imagined. In our domain of teaching & learning schools shut and to the best of their abilities moved on-line. Technology, which has not to date led to the widescale re-imaging of education which at least some in the Constructionist community have long argued for, overnight became central to the way in which teaching and learning takes place. Teachers, many of whom belonged to the "late majority" of technology adopters, have availed of the myriad of professional development opportunities which have sprung up in response to the move to on-line and are embracing the use of technology on a scale which would have been unimaginable a few months previously.

This transition to on-line has of course not been smooth. The inequalities of the digital divide have been shown in stark relief and far too many students, and their families, have been caught on the wrong side of that divide. It is very difficult to learn, or study for major exams, in a bedroom you share with two siblings, using only a mobile phone and a costly data package!

Furthermore the adoption of technology for on-line teaching has in many cases followed a substitution paradigm with the traditional "chalk and talk" paradigm now taking place on a different medium. In many cases even synchronous classes proved a bridge too far with technology being used to disseminate lessons and collect homework.

While these observations are drawn largely from the Irish experience and are based on (well informed) anecdotal evidence we expect that the situation is not untypical of what is happening in many places and will in due course be backed-up by a more rigorous research evidence base.

A phrase which is commonly brandied about at present is the “new normal” which refers to how all aspects of society will operate as we await a vaccine for the virus, attempt to recover from the economic shock and avail of the opportunity to learn from the experience and re-imagine how things can be done better for everyone, and for the planet, going forward. Surely education must be central to this re-imaging process and the challenges for the Constructionist community, as alluded to in the call for conference submissions, are to outline what role our pedagogy could play in the “new normal” and to endeavour to make sure those ideas make the difficult transition from a minority of innovative places of learning to the mainstream.

This set of proceedings will sit in the archive of Constructionist conferences, going back to Paris in 2010, and in the wider Constructionist literature as a check-point reflecting the thinking and activity of the community just prior to the pandemic. It should, at the very least, make for interesting reading in the years to come when we look back and reflect on the shape of the educational new normal and the role which Constructionism plays in it.

As the Irish poet, W.B. Yeats, put it, writing in a different context, *“All is changed, changed utterly.”* It remains to be seen what sort of *“terrible beauty is born”*.

We would like to thank: the Programme Committee for reviewing all the submissions received, Jane O’Hara for administrative and planning support, the “three wise men”, and all the authors who took time to revise their submissions when there was a lot else going on!

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Dublin 26th May 2020

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Twenty Things to Make with Biology

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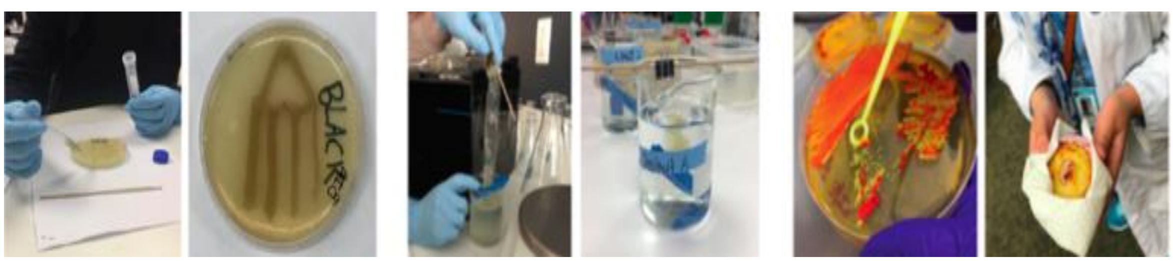
Abstract

A 1971 memo by Papert and Solomon introduced twenty things to do with a computer which became the foundation for constructionism. In this paper, we propose bringing constructionist activities into making with living materials. Significant developments in tools and methods have turned biology into a design science: it is now possible to make things *with* biology—or biodesign—rather than just observing processes and behaviours. Our list of twenty things to make with biology includes examples from making colours, toys, games, insulin, batteries, sensors and more. In the discussion, we review how making with biology addresses key affordances of constructionist learning: "tinkerability," the ability to experiment; "perceptibility," the immediacy of feedback on learning process; "expressivity," the personal customization of products; and "usability," the ability to use learning designs in everyday contexts. We conclude with an overview of accessible and affordable tools available to K-12 education.



A. BioLogo design using bacterial pigment to make colours: (left) 'Painting' with bacteria; (right) A completed logo design. Source: Kafai et al., 2017.

B. BioSensor construction using bacteria as detector: (left) Putting the transformed bacteria into the dialysis bag; (right) The completed sensor contraption. Source: Kafai et al., 2017.

C. BioCake using yeast with vitamin A: (left) Petri dish with mixed colonies of yeast cells; (right) Student holding her freshly baked enriched cake. Source: Walker et al., 2018.

Figure 1. Making with Biology: Colour (A), Sensor (B), and Food (C).

Keywords

Biology, Making, Materials

Introduction

In 1971, Seymour Papert and Cynthia Solomon wrote a memo titled "Twenty Things To Do With A Computer," where they outlined a bold vision of how children could be introduced to programming, the more general knowledge of computation, and other formal subjects ranging from physics to music. The programming language LOGO would allow learners to converse and interact with a computer, and in the process introduce new ways of learning. In the memo, they suggested a variety of activities children could program in LOGO: making a turtle draw images on paper by programming a pen to lift up and down; programming behaviours so that the turtle could follow along walls and navigate corners in a room; engaging in geometry by writing program to draw spirals; making an online movie by programming change of petals in a flower; programming sounds to play a song; playing a game called Spacewar and then programming a new game; and many more. The last item on the list was called "recursion line" asking the reader to come up with twenty more things to do with a computer!

These ideas became the foundation for *Mindstorms,* the book that Papert (1980) would publish a few years later. Here, he introduced the education community to how computers could be used by children for learning about powerful ideas such as recursion, variables, mathematics, and cybernetics among others. The activities suggested—a computer that could carry out such processes as spinning motors, activating electromagnets, switching on lights, or even reading the state of light sensitive cells—must have seem far-fetched for most readers in the early 1970's. But Papert and Solomon insisted that it was easy to make the computer do all these things, and readers didn't need to know *how* the computer worked. Instead they needed to describe *what* they wanted to do in an appropriate language such as the LOGO programming language, as if they wanted to give instructions to a person. They concluded while some might balk at the current high cost, that the price of terminal time could come down significantly if more schools would sign up, and that ultimately, every child should be entitled to experience the world of computers.

In "Twenty Things to Make with Biology" we are extending the constructionist vision of engaging learners to converse, interact and design with living materials in new ways. While computers in the 1970's introduced computation with 0's and 1's, today's world of biology as design uses A's, T's, C's, and G's as their building blocks. In bioengineering, designers can make their own DNA—gene by gene—and then grow their designs into real applications by inserting them into living things such as microorganisms (Endy, 2005). In the following sections, we describe twenty things to make with biology. More than half of our suggestions have already been implemented with middle and high school students in schools and community labs. Some of these activities make use of everyday materials such as yeast, kombucha, soil, sand, and tea found in people's homes and pantries while others use mycelium (i.e., mushroom roots) or Escherichia *coli* bacteria which can be ordered online. In some instances, they require lab setups such as petri dishes, plastic droppers, and incubators while others use home kitchen materials such as pots of warm water or baking sheets. Most importantly, readers not need think about how cells will actually make the things but more about how they can use general biology and practical knowledge to design new applications. In the last section of this paper, we share some of our observations about how *making things with biology* is either the same or distinct from doing things with a computer.

Twenty Things to Make with Biology

1. Create a Smell

In *Eau that Smell* learners can genetically modify bacteria (e.g., Escherichia *coli*) to selectively emit a banana scent at different stages of cell growth (Kuldell, 2015). Smell functions like an indicator and showcases how genetic perturbations can be introduced and programmed very precisely. It also illustrates how synthetic aromatics or flavour food additives can be sustainably produced.

2. Grow a Brick

The company BioMason (2019) grows bricks by the thousands by combining sand and bacteria in a cast. By feeding the bacteria with a liquid cocktail that generates a binding substance and letting them dry for a few weeks, the bricks are formed. This approach uses far less energy than existing methods that require stone/mineral extractions, transport and kiln for curing.

3. Bake Enriched Food

Take a plasmid, a pre-coded segment of DNA, and insert it into yeast (Saccharomyces *cerevisiae*), to reprogram the cells to produce beta carotene, also known as vitamin A (Kuldell, 2015). Growing more yeast with Vitamin A this way can be used to bake a cake, or bioCakes (Walker et al., 2018), which is enriched with important nutrients.

4. Build a GMO Detector

To find out whether food contains Genetically Modified Organisms (GMOs), collect DNA from uncooked fruits or vegetables and add a mix of DNA strands that react with known GMO elements. If your food contains a GMO, the DNA strands are designed to fluoresce in the presence of UV light (GMO Detective, 2019).

5. Feed a Battery Light

To make a battery, collect a soil sample from your garden. Place the soil in a container that has conductive chicken mesh at the bottom, attach to this chicken mesh an insulated wire made of zinc, and connect a LED at the top. Take a second mesh/chicken wire—this time attached to an insulated copper wire—and place it at the surface of the soil. Provide water for the microbes in the soil. After two days, the bacteria residing in the lower part of the container where there is much less air will produce enough electricity to turn on the LED light (Magical Microbes, 2019).

6. Grow Insulin

The Open Insulin project (2019) has reprogrammed yeast to produce human insulin at large scales. The yeast needs to be grown in standard nutrient broth to produce purified insulin hormone molecules. This makes insulin very compatible with humans and more affordable.

7. Spin Fibers for Fabric

Spider silk is not only light weight, but also incredibly strong which makes a very durable and versatile fabric. To grow silk with similar features, bacteria are genetically reprogrammed to produce the strong and elastic collagen proteins found in spider silk. This is protein is then purified, dried and spun into thread to weave fabric. Adidas (Wired Magazine, 2017) and The North Face (Forbes, 2019) already used this approach for making shoes and jackets.

8. Dynamic Colors

Make a canvas covered with colourful yeast nutrients that change colours overtime as the yeast consume, grow, and age (Yeast Art Project, 2019). Yeast cells are very good at producing beta carotene that can be scrambled up by adding a hormone to produce various pinks, violets, blues, and even black.

9. Power Gears

Rod-shaped bacteria known as Bacillus *subtilis* can be assembled to rotate microscopic gears and control machines. Tiny gears and screws can be assembled and placed in a liquid environment to keep the bacteria alive and mobile. When enough bacteria are present and move in a common direction—this is called a swarm—they can collectively force the gears to move in predictable directions. Photosensitive bacterial swarms can also be directed by using light (Sokolov et al., 2019).

10. Biodegradable Home Goods

Grow biodegradable home goods and accessories like pots, pencil holders, lamp shades, picture frames and other accent pieces (Ecovative, 2019) using mushroom roots, also called mycelium. Once Mycelium are fed flour and water, they become active after a few days. To make a shape, fill a container with active mycelium and mix in small wood chips, saw dust, or other materials. After a week, the shape is ready and can baked at low heat to stop the mycelium from working.

11. BioSensors

Bacterial cells can be genetically modified and grown to function as sensors and start to glow in the presence of a contaminating substance. Students can build their own sensor with dialysis tubing (see figure 1b) wherein they put the bacteria and place in a cup filled with water that may or may not have the contaminating substance (in this case a sugar called arabinose). If the cup contains arabinose, then the cells in their biosensor tubes will glow under ultraviolet light (Kafai et al., 2017).

12. Kombucha Plastic

Make a bioplastic using a blend of yeast (Saccharomyces *cerevisiae*), kombucha bacteria (Gluconacetobacter *kombuchae*), and lukewarm black tea in a pan. These two organisms work together to produce a biofilm or bioplastic in the presence of nitrogen-rich substances like tea (Shade et al., 2011). After waiting for about 2-4 weeks, a 1-2 inch layer will form in your pan which can be dried and then shaped in many ways.

13. Make an RGB Device

Bacteria such as Escherichia *coli* can be reprogrammed to glow in red, green, and blue (RGB colours) when exposed to ultraviolet light (Tsien, 2010). These glowing bacteria can be put together in different combinations to create new colours and designs. As long as the bacteria are fed, they will continuously produce these fluorescent colours.

14. Play a Game Under the Microscope

Single-celled amoeba-like organisms called Euglena *gracilis* are mobile and respond to specific light colours (Lee et al., 2015). It is possible to control their direction. This means that with the right configuration, two players could race to direct their organism across a finish line or compete to trap (or guide) them in a maze. The only thing needed here is a microscope to visualize the race.

15. Make Vegetables Savory

The Impossible Burger is made out of plants but tastes like a burger made of beef (Burger King, 2019). This is made possible by adding the DNA for a protein found in red blood cells, called heme, in plants. Then plant-based produce like tomatoes are not only more savoury, but also contain more protein content.

16. Dye Fabric

Manufacturing fabric colours like indigo with petrochemicals is harmful to the environment. The bacteria Streptomyces *coelicolor* can produce a large amount of rich, long-lasting, and environmentally friendly indigo pigments to dye thread and whole fabrics (Faber Futures, 2019).

17. Make a Photocell

Phylum algae are very effective at producing electricity using sunlight. These cyanobacteria use photosynthesis to generate this energy. They can be collected and placed in printer cartridges to print on conductive paper. By adding a transistor to a printed circuit arrangement, they can be powered and create a sustainable and recyclable household energy source (Phys.org, 2017).

18. Grow Construction Kits

Many construction kits are made of plastic that is non-degradable. By using mushroom roots (i.e., mycelium) and fermented kombucha, students can grow biodegradable materials to make a biodegradable toys such as a kaleidoscope, doll clothing made with kombucha bioplastic, or Lego compatible 3D printed wings covered in kombucha bioplastic (GIY Biobuddies, 2019).

19. Engage in Critical Discussions

Making things with biology can raise a whole host of thorny issues related to transparency, impact on environment and humans. Those include, evaluating the risks, impact, safety and moral acceptability of designs such as perils of plastic waste in the toy industry and the value of sustainable manufacturing. There are a number of topics to discuss around these issues including those related to food security, environmental sustainability, agriculture, and climate change to name a few.

20. Recursion Line

Think up twenty more things to *make with biology*!

Discussion

We described a wide variety of things that learners of all ages can make with biology using living materials. One attraction of many digital or physical constructionist activities—such as designing games, printing in 3D, building robots, or crafting electronic textiles—is that students are generating, re-making, or augmenting artifacts with physical and digital tools that are already present in their environment. While biomaking also involves materials and tools that are present in students' homes and science classes, the actual fabrication processes and outcomes are distinct in ways that confront core tenets of constructionist theory. Making things with biology differs in sometimes significant ways in terms of tinkerability, perceptibility, expressivity, and usability (Lui, Kafai, Walker, Hanna, Hogan, & Telhan, 2019). In the following sections, we discuss these distinctions but also similarities in more detail and what insights provide for constructionist learning designs and tools in making with biology.

How Making with Biology is Different

Constructionism has always valued tinkering (Resnick & Rosenbaum, 2013), a playful, experimental iterative style of engagement wherein makers are continually reassessing their goals, exploring new paths and imagining new possibilities, and having "a conversation with the material" (Schön, 1983). However, tinkering with biology is much more difficult since microbiological processes involve liquids and require a full run of the entire lab procedure before one can see any result. In biology, processes often occur in a holistic fashion and thus fixing a 'mistake' frequently means doing a lab procedure all over again and waiting for the result, whereas tinkering in engineering and coding involves discrete processes such as iterating on a gear mechanism or developing a specially defined procedure. The specificity of lab procedures and limitations of materials make it somewhat difficult to engage with on-the-spot messing around so popular in maker activities on and off the screen (Lui, Anderson & Kafai, 2018).

Another valued aspect in constructionist activities is that computer or physical designs can yield immediate feedback either on the progress or results of making. For instance, a coder can see the result of a bug they fixed in a program whereas in biomaking this process occurs more slowly. While microorganisms grow quite rapidly, it often takes hours or more for any genetic transformation to yield an outcome. More importantly, due to scale and colourlessness of the microorganisms, learners often cannot immediately see the outcomes of their designs or changes. In making with biology, it is also much more difficult—but not impossible—for learners to personalize artifacts or designs. 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, learners must often (but not always) depend on existing protocols and materials developed by experts.

Finally, constructionist activities foster designs that learners or others can immediately use such as playing a game made in Scratch (Resnick, Maloney, Monroy-Hernández, Rusk, Eastmond, Brennan, Millner et al., 2009), making music on a banana piano made with MaKey MaKey (Silver, Rosenbaum, & Shaw, 2012) or a turn-signal hoodie made with the LilyPad Arduino can be worn while biking and signal directions with flashing LEDs (Buechley, 2006). In biomaking, usability comes with its own set of constraints. Some living designs can perish at some point, so careful consideration must be taken to, when necessary, keep the organism alive, such as supplying them with enough nutrients and at appropriates temperature. From this perspective, making with computers affords numerous ready-made situations for usability while biomaking has not yet reached this point of development in its short history.

What Making with Biology Shares with Things To Do with a Computer

We also saw similarities and connections to constructionist learning. While making with biology activities are limited in tinkering with regard to the scripted steps of the lab procedures needed to create the right conditions for, as an example, bacteria to flourish and produce a desired result, the actual hands-on construction and crafting of applications provides considerable degrees of freedom. For instance, students engage with crafting while: “painting with bacteria” by using hot glue guns to mold shapes for their petri dish logos (Kafai et al., 2017), making kombucha plastic and leather clothes for their paper dolls (GIY Biobuddies, 2019), or even colouring fabric.

We also noticed that in many of the suggested applications bacteria were chosen that would reveal a visible change, thus promoting the “perceptibility” dimension prominent in constructionist activities. For instance, in Eau that Smell (Kuldell, 2015) bacteria signal change by emitting a banana smell, in Faber Futures (Faber Futures, 2019) and the Yeast Art Project (Yeast Art Project, 2019) microorganisms signal change when they produce pigments, or—in another case luminescence (Tsien, 2010) to make outcomes more ‘visible’ to students. While not all biomaking activities provid the expected feedback, it was sometimes precisely the lack of feedback (beakers that did not glow and “stinky” bacteria) that provided contexts for conversations around the science of the process.

Finally, in terms of usability making with biology involved product designs that reached beyond the personal. For instance, in BioLogo, it involved a company focused on sustainable product design, while BioSensors involved researching contexts in which sensing pollution would be of importance, and BioCakes involved thinking about food products that could benefit from nutritional enrichment. It is here where we saw the imagination of students flourish as they recognized the usability—both personal and societal—of their designs. Other examples include Ecovative (Ecovative, 2019) and GIY Biobuddies (GIY Biobuddies, 2019) that both leverage mycelium properties to build a whole swath of products including furniture, home accessories, toys and constructions kits. Or bioMason (bioMason, 2019) and the North Face (Forbes, 2019), who use bacteria to construct building material and clothing. These examples illustrate new frontiers in biology wherein products are not only usable, but they also provide a space for student discourse around manufacturing, sustainability, material life cycles and their collective impact on the planet.

How to Make Things Happen

The development of programming languages and construction kits that let learners do things with computers both have been a driving force in promoting constructionist learning. Previous constructionist efforts focused on making digital designs by controlling a turtle on the computer screen or on the floor. The design of portable and programmable bricks (Resnick, Martin, Sargent & Silverman, 1996) allowed learners to move designs into the physical world and build autonomous creatures no longer tethered to terminals.

Recent developments of simple to use portable lab tools make it possible for K-12 students to genetically alter a wide range of cells for designing a variety of applications. For instance, the *biomakerlab* (Kafai et al., 2017) is a low-cost portable wetlab device that makes it possible to easily genetically modify and grow bacteria cells. Another even simpler example is *BioBits* (Stark et al., 2018) which eliminates cells altogether and provides freeze-dried pellets made of cellular parts that, when hydrated, assembled, and incubated, express unique gene designs, such as a full palette of colours that fluoresce in the presence of ultraviolet light. Other examples include Bento

Labs (Bento Labs, 2019) which provides a portable wet lab device that enables users to construct, isolate, enrich, and analyse genetic parts that can later be introduced into living cells. Amino labs (Amino Labs, 2019) is yet another example that enables young students to transform (i.e., genetically modify), grow and analyse newly engineered organisms.

Some work is even targeting younger students—namely elementary grades. CRISPEE (Verish et al., 2018) is an example of such an effort as researchers developed a low cost block-based simulation device that allows young learners to mix and match wooden blocks in a device that illuminates a simulated firefly bulb with a colour that is representative of the block combinations created by the user. This activity is meant to help young learners understand what synthetic-based genetic modifications are as a concept and the various ways it impacts living things and their traits. When learners introduce their own genetic perturbations (represented by different block combinations), they gain a sense of how to manipulate and—to an extent—control the design of living things.

Our examples of making with biology provided a glimpse into the foreseeable future in which we engage students with 'making' or 'growing' their designs in petri dishes—just like several decades ago students were first invited to making or 'coding' their designs on computers. Realizing making with biology in K-12 education will require significant efforts but learners themselves have already taken charge. In 2019, for the first time, two teams of high school students participated in the BioDesignChallenge which brings together international teams of college students who compete in developing biodesign applications that solve global challenges related to the environment and manufacturing sustainability. To everyone's great surprise, one high school team of three girls took home the first runner up by creating a biodesign toy kit for other K-12 students. The kit provided microbial-based and mushroom-based packaging for new toy designs to address the perils of plastic waste in the toy industry with more sustainable manufacturing. Indeed, making with biology can introduce learners to 21st century ways of doing and thinking just like computers did in the era before.

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