SynFlo: A Tangible Museum Exhibit for Exploring Bio-Design

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ABSTRACT
We present SynFlo, a tangible museum exhibit for exploring bio-design. SynFlo utilizes active and concrete tangible tokens to allow visitors to experience a playful bio-design activity through complex interactivity with digital biological creations. We developed two versions of SynFlo: one that combines active tokens with real concrete objects (i.e. labware) and one that consists of only abstract active tokens. Results from an evaluation in a museum indicate that both systems support learning. We discuss design choices for biology education tools to overcome confounders of biology and facilitate positive engagement and learning.

Author Keywords
Tangibles; active tokens; museum; children; bio-design;

ACM Classification Keywords
H.5.m. Information interfaces and presentation: User Interfaces---input devices and strategies, interaction styles.

INTRODUCTION
Research on visitor learning in museums suggests that interactivity promotes engagement, understanding, and recall of exhibits [4]. However, creating interactive, tangible, and exploratory educational activities in biological sciences is confounded by several factors. These include long time scales, complexity of the topic, and the unique behaviors of biology, many of which occur at the nanometer level and are subject to unintuitive physics. The existing hands-on educational activities in schools and museums often reflect these obstacles in their traditionally phenomenon-focused, time-consuming nature.

Several educational museum exhibits have demonstrated the potential of fostering learning through playful multi-touch and tangible interactions with biological concepts such as evolution and phylogenetic trees. While these exhibits allow users to explore and engage with large biological datasets [13, 28, 33], our goal is to allow users to design and tinker with synthetic biology. We seek to demonstrate concepts of biological engineering by creating an interactive platform for exploring bio-design. Providing a set of tools to design, tinker with, and build has become an accepted framework for creative learning, especially for skills required to approach unfamiliar challenges [25]. Though long common in the more tangible fields of mechanical and electrical engineering, acknowledged experts in the bioengineering field echo these sentiments [29]. While there are examples of synthetic biology software and games written to convey the design of new organisms [1, 12], there is currently no platform for non-scientists that simulates tinkering and creating with biological material outside a wet laboratory setting.

Creating an interactive platform for exploring bio-design brings into direct conflict the goals of design and tinkering (tangible, responsive, and open ended) and the confounders of biology (invisible, unintuitive, slow, and prescriptive). Though using authentic tangible labware is desired, virtual augmentation is necessary to bring the time and size scales into the range of a play session. In this paper, we present SynFlo, a tangible museum exhibit for exploring bio-design. SynFlo utilizes active tangible tokens, programmable physical objects with integrated display, sensing, or actuation technologies [31], to bridge time and size scales in order to allow visitors to experience a playful bio-design activity using a collaborative platform for complex interactivity with digital biological creations.

We describe the two-year long iterative design process of SynFlo and its evaluation in The Tech Museum of Innovation. This paper presents four main contributions: (1) Lessons from the iterative design and evaluation of a tangible museum exhibit for bio-design; (2) New tangible techniques for interacting with biological material using active tokens and real lab equipment; (3) Findings from an evaluation in a museum; and (4) Discussion of design choices that facilitate and constrain positive engagement with a tangible exhibit aimed at communicating complex scientific concepts to a wide audience.

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RELATED WORK

Constructionist Learning

We designed and evaluated SynFlo in collaboration with The Tech Museum of Innovation, whose philosophy is to "inspire the innovator in everyone" by being a community in which people can learn by exploring and creating [3]. The Tech's philosophy and our design of SynFlo are inspired by Papert's Constructionist educational framework [23]. Constructionism states that children learn deeply when building their own meaningful project in a community of learners and when reflecting on the process. This framework is rooted in Piaget's [24] constructivism – which conveys the idea that children actively build knowledge through experience – and the related "learning by doing" approach to education. Constructionism is particularly suitable to learning in synthetic biology, where students are encouraged to construct understanding and knowledge as they work to solve real-world problems using a toolkit of biological parts [2, 26].

Papert discussed that well-designed constructionist activities have 'powerful ideas' embedded in them, central concepts within a domain that are both epistemological and personally useful, interconnected with other disciplines, and have roots in intuitive knowledge that a learner has internalized over a long period of time [23]. Our design of SynFlo integrates powerful ideas from the domain of synthetic biology (e.g. abstraction, modularity, standardization), which are interconnected to multiple disciplines (e.g. engineering, design) and build upon the intuitive understanding that children develop by playing with construction toys. SynFlo also demonstrates connection to real world problems (e.g. toxin detection).

Tabletop and Tangible Interactions for Informal Learning of Biological Concepts

Several tangible and tabletop interfaces demonstrate the potential of applying TEI approaches for learning biological concepts. G-nome Surfer [27] and GreenTouch [32] are tabletop multi-touch applications for collaborative exploration of genomic and phenology databases. Both applications support inquiry-based learning and allow for open-ended data exploration but are designed for college level formal learning environments.

The DeepTree exhibit [13] is a multi-touch tabletop that allows users to explore an interactive visualization of the Tree of Life. *Fishing with Friends* [8] is a multiplayer exhibit where visitors play in a simulated fishing environment to learn about overfishing. TrapIt! [18] uses a touchscreen to control light beams that interact with live cells. While these touch interfaces support collaborative, playful, and prolonged experiences for exploring biological phenomena, our approach utilizes gestural and tangible interaction to allow users to create with biology.

Much research has highlighted the benefits of tangible interaction for learning [5, 15, 21]. However, incorporating tangibles in museums introduces additional complexities, while the benefits of tangibles are not always clear. Horn et al. [14] discuss several tangible and non-tangible versions of interactive learning tools and conclude that it is often a combination or hybrid of the two styles that is most effective. Ma et al. [20] compared tangible and graphical versions of an exhibit and found that while the tangible version attracted more visitors, there was not necessarily a difference in the visitors' experience with the exhibit. Considering the trade-offs between tangible and non-tangible systems in informal learning scenarios, we chose to design and compare two different versions of SynFlo.

Tangible Interaction with Active Tokens

To bridge the time and size scales of bio-design, SynFlo utilizes tangible active tokens. Several tangible interfaces demonstrate the potential of using active tokens for complex activities. Tangible Video Editor [35] uses active tokens for video editing. Other tangible interfaces have explored the use of active tokens for query formulation [17, 30]. Eugenie [11] is a tangible user interface for bio-design that utilizes active tokens to represent BioBricks. Unlike SynFlo, which is designed for a general audience, Eugenie was designed for advanced users who are synthetic biologists. Valdes et al. [31] presented a vocabulary of user-defined gestures for active tokens and a characterization of the design space. Our design iterations were informed by this work.

APPLICATION DOMAIN AND DESIGN GOALS

Synthetic Biology

Synthetic biology is a burgeoning field that couples engineering and biology. It strives to apply basic engineering principles such as standardization, abstraction, and modularity to bio-design. Complex genetic programs are broken down into standardized biological parts called BioBricks and are used like "Lego Bricks" to build living organisms with new properties. Synthetic biologists aim to solve diverse real-world problems in areas such as agriculture, medicine, environmental decontamination, and fuel through bio-design.

E. Chromi

SynFlo draws upon a classic synthetic biology project called E. Chromi [9], in which genetically engineered E. coli bacteria act as bio-sensors, indicating the presence of certain toxins in their environments. The experimental protocol of E. Chromi consists of the following high-level steps: 1) Combining standard biological parts (BioBricks) to create a genetic element capable of producing a specified color in response to the presence of a particular toxin; 2) Inserting the new genetic element into a plasmid, a circular DNA strand that replicates independently from chromosomal DNA; 3) Transforming E. coli bacteria with the engineered plasmids; and 4) Testing the ability of the modified bacteria to sense the presence of a toxin.

SynFlo combines tangible and digital representations to allow users to experience an interactive and playful simulation of the E. Chromi bio-design process. Figure 1 illustrates interaction with the current prototypes of SynFlo.

Design and Learning Goals

We designed SynFlo over a two-year iterative process that included close collaboration with synthetic biology educators and researchers. Together, we defined the following learning goals for SynFlo, which focus on illustrating core concepts of synthetic biology: L1) abstraction—the representation of genetic materials as standard biological parts called BioBricks or genes; L2) modularity—the construction of biological systems composed of reusable mix-and-match BioBricks; L3) standard protocols—the use of predefined standardized laboratory procedures to ensure safety and successful replication of results. We also aim to demonstrate an application of biological engineering - toxin detection (L4).

Our design goals for the current prototype of SynFlo were informed by these learning goals and influenced by The Tech's educational philosophy which values hands-on open-ended learning experiences: G1) Conveying the excitement and concepts of biological engineering by allowing people of all ages to design with biology; G2) Communicating the basic rules of bio-design: select a gene (i.e. BioBrick) with a particular behavior, add gene to a plasmid, insert plasmid to a living cell, test for expected behavior; and G3) Facilitating the development of inquiry skills through a collaborative and playful experience.

DESIGN ITERATIONS AND RATIONALE

Iterative Design

The tangible interface we developed for SynFlo allows users to experience a bio-design activity based on the E. Chromi experiment and takes inspiration from the tension between metaphor and process. The metaphor of BioBricks, DNA sequences with specified functionality used to design and assemble synthetic biological circuits, is widely used within bio-design [2]. It embodies three important engineering principles critical for bio-design: abstraction, standardization, and modularity. However, novel biological designs are incorporated into living cells (e.g. E.coli cells) in an elaborated physical process. This process takes place in a wet laboratory and requires specialized lab equipment, biological reagents, and mechanics.

To date, we have developed and evaluated four different prototypes of SynFlo that use Sifteo cubes as active tangible tokens. We chose to use Sifteo cubes because their form factor reinforces the metaphor of BioBricks and because they support a variety of gestures.

The first two prototypes of SynFlo were not designed for a museum environment but rather for outreach programs for high school students where the interactive activity was preceded by a short lecture introducing synthetic biology. The *first prototype* [26] consisted of triplets of Sifteo Cubes 1.0, a tabletop computer (SUR 40), and passive tangible tokens that represented environmental toxins. Each triplet of Sifteo Cubes represented a collection of genes, a plasmid, and a bacterial cell. We represented the testing environment for newly engineered E.coli using a tabletop computer. The evaluation of this prototype indicated that although we designed SynFlo to utilize gestures that mimic physical actions performed in the lab, users did not always understand these metaphors. This observation led to a redesign which resulted in a *second prototype* [34], which embedded the Sifteo Cubes within evocative concrete tangibles that represent lab instruments and afford physical actions such as shaking, pouring, and flipping. The toxin tokens and the interaction with the tabletop remained the same.

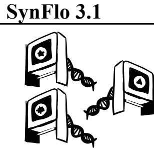
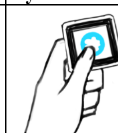
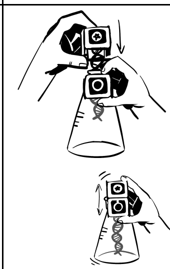
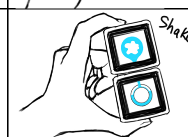
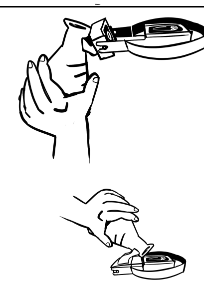
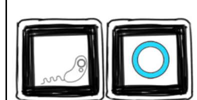
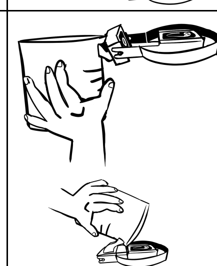
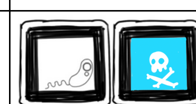
	SynFlo 3.1	SynFlo 3.2
Step 1: Choose a toxin-sensing gene.		
Step 2: Transfer the gene into a plasmid by neighboring pieces and shaking.		
Step 3: Transfer the plasmid into the bacterial cell by pouring (SynFlo 3.1) or by neighboring cubes (SynFlo 3.2), After the plasmid is transferred, the bacteria changes to show the new plasmid.		
Step 4: Introduce a toxin to the bacteria by pouring (SynFlo 3.1) or neighboring the cubes (SynFlo 3.2). The toxin appears on the bacteria cube and if the bacterial cell has the gene that senses that toxin, the cell turns color.		

Figure 1. Interaction techniques: SynFlo 3.1 and SynFlo 3.2.

This paper introduces two new prototypes of SynFlo (Figure 1), which were redesigned for a museum environment. The main goal of this redesign was to allow people of all ages to create with biology using SynFlo. The two new prototypes operate in a similar manner to each other, but highlight the tension between metaphor and process. The *third prototype* (SynFlo 3.1) replaces the tabletop interaction with tangible interaction using Sifteo cubes attached to *authentic* labware such as beakers and flasks. The exhibit consists of three token quadruples. Each quadruple consists of several genes (i.e. BioBricks), a plasmid (attached to a flask), a bacterial cell (attached to a Petri dish), and a toxin (in a beaker). The tangible interactions draw upon the affordances of the labware and imitate physical steps performed by biologists in the lab. By eliminating the tabletop interaction we focus users on the core aspects of bio-design: selecting BioBricks for accomplishing a certain behavior and inserting them into a living cell. The elimination of the tabletop also shifts the focus from building and deploying to building and testing *in-vitro* on a smaller, immediate scale.

In order to examine the role of authentic concrete tangible tokens (i.e. labware) in positive engagement and learning of bio-design concepts, we developed a *fourth prototype* (SynFlo 3.2, Figure 1), which uses *abstract* tangible tokens. The system functions in the same way as SynFlo 3.1, but instead of having the Sifteo cubes attached to authentic labware, the user performs the interactions with just the cubes themselves. We compared these prototypes in our observational study to better understand the tension between metaphor and process: SynFlo 3.1 utilizes authentic and concrete tangible tokens to simulate the physical *process* taking place in the wet laboratory; SynFlo 3.2 stresses the *metaphor* of BioBricks emphasizing the principles of abstraction and modularity. The procedure and results of comparing these prototypes are described in the Observational Study section.

Design Rationale

In this section we highlight design features and choices which we have made to address the challenges of creating an interactive exhibit for bio-design and to facilitate learning. Our design choices were informed by our iterative design process as well as by design frameworks for learning with tangible user interfaces.

Active Tokens

One of the core challenges of creating an interactive exhibit for bio-design is bridging size and time scales. Exploratory educational activities in bio-design require long time scales for cell transformation and demonstration of the unique behaviors of living cells that occur at the nanometer level. To overcome this challenge we chose to utilize Sifteo Cubes as active tangible tokens, which can provide the virtual augmentation necessary to bring the time and size scales into the range of a short human play session. The integrated displays enable us to create an experience that is fully embodied [10] (i.e. the state of the tokens is fully embodied in the tokens themselves). We utilize animations, which illustrate interactive behaviors and provide feedback on physical actions. Cells represented by Sifteo cubes are animated to reflect their living nature. Changes that occur in response to physical actions (e.g. shaking) reflect progression over time (e.g. dripping) in a playful manner.

Gestural Interaction

Making core concepts of synthetic biology and bio-design accessible and understandable to non-scientists is often challenged by limited access to biological technologies. The use of active tokens allows us to simulate bio-design by providing a set of tools for creating with biology outside of the laboratory. To mimic physical aspects of laboratory work, we chose to use Sifteo cubes as active tokens because they support a variety of gestures including moving, shaking, flipping, rotating, and neighboring. The gestural interaction techniques we developed for SynFlo (Figure 1) reflect the elaborated physical process in which biological designs are incorporated into living cells.

Research in cognitive sciences indicates that physical actions impact thinking and learning. Physical actions made with a physical model were shown to be tightly coupled with emerging conceptual models, helping to leverage the connection in the brain between motor, perceptual, cognitive processes in the development of insights [7]. Based on these findings, we designed SynFlo to facilitate *learning through doing* by utilizing gestural interactions to help users develop a conceptual model that is connected to the scientific concepts and processes of bio-design. We also aimed to support *learning through observation* by defining gestural interactions that are visible and legible.

Concrete tangible tokens

Considering the complexity of the domain, another challenge is to create an exhibit that is apprehendable for a diverse audience. To provide context and guidance for visitors, we utilized authentic tangible tokens, real labware such as beakers and flasks, which we augmented by attaching to active tokens. We drew upon both the symbolic meaning and the physical affordances of these objects to support the interpretation of abstract concepts [6]. We then designed physical actions for manipulating the active tokens, which imitate physical gestures performed by biologists in labs.

Martin and Schwartz [22] provide four ways in which physical actions support learning and cognition: induction, off-loading, repurposing, and physically distributed learning. We used these categories as a framework for considering how tangible and gestural interactions with these active tokens might support our learning goals. SynFlo 3.1 (Figure 1) incorporates concrete tangibles (i.e. real labware) to support learning through *induction* - users do not have stable ideas, but they are acting in a stable environment that offers clear feedback and strong constraints that can guide interpretation. SynFlo 3.2 (Figure 1) only uses abstract tangible tokens which resemble blocks to facilitate *physically distributed learning* - user's ideas and the environment are both adaptable, users may interact with their environment and tinker with the tangibles without knowing exactly what steps they need to take. Our observational study examined how users manipulated, and learned with these different prototypes.

Multiple access points

Most museum visitors come in groups, thus a challenge for designers is to streamline visitor groups while supporting collaborative learning. We designed SynFlo to be manipulated by more than one person at a time, providing multiple tokens that serve as access points to the exhibit [16]. The latest prototypes of SynFlo (versions 3.1 and 3.2) consist of three token quadruples that can be remixed. This structure allows for distributed control, preventing one visitor from controlling the exhibit. The visibility of the gestural and tangible interactions allows users to see what others are doing and how different tokens are manipulated.

Facilitated Short Play Session

Finally, in order to streamline visitors around the exhibit, we designed the Synflo activity to be a short play session, about three minutes long. A challenge we faced was to create an activity that is exciting and engaging while at the same time exposes users to the complexity and rules of bio-design within the short session. We designed SynFlo so that it encourages initial engagement through play and tinkering. The system provides dynamic feedback at each stage. The last stage of the activity allows visitors to test their modified cells (E.coli) and based on the feedback reflect on the results. In addition to self-reflection, we designed SynFlo to provide facilitators (e.g. museum volunteers) with opportunities (e.g. visible gestures or system responses) to initiate a conversation about bio-design.

OBSERVATIONAL STUDY

The goal of our observational study was to explore how our design decisions affected the interactions with and around the system. In particular we aimed to understand the role of SynFlo's tangible and gestural interactions in facilitating engagement, collaboration, and learning. To study the impact of using concrete tangible tokens (i.e. authentic labware), we compared two different prototypes: SynFlo 3.1, which uses concrete tangible tokens, and SynFlo 3.2, which uses abstract tangible tokens (Figure 1).

Figure 2. Synflo study setup in the museum

The evaluation of SynFlo took place in The Tech Museum of Innovation over a weekend. We had a table set up with the system and printed visual guides (Figure 2, 3). Two facilitators sat behind the table interacting with visitors while a video camera recorded continuously.

We ran the study on a Sunday for 1.6 hours with SynFlo 3.1 (concrete tangibles) and 2.3 hours with SynFlo 3.2 (abstract tangibles). For each visitor group, the facilitators introduced the fact that biologists can engineer living organisms and the biological terminology, pointed the visitors to the visual protocol instructions (Figure 3), and allowed them to explore while engaging them with questions about what they think is happening. The facilitators would step in to help visitors with challenging interactions or point them to the instructions. After the visitor had successfully engineered a bacteria, the facilitators would ask child visitors their age, questions to gauge their understanding of the biological process, and to rank on a scale of 1 to 10 how difficult they thought the exhibit was and how much they enjoyed interacting with it.

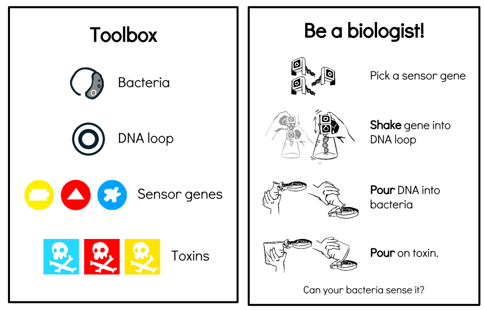


Figure 3. Toolbox and interaction guide (version shown here for SynFlo 3.1)

Data Collection and Analysis

Video recordings of the evaluation were split into segments based on interaction group. We used Atlas.ti to analyze 280 minutes of clips using a video coding scheme that was developed iteratively and included 31 codes. Inter-coder reliability based on 30% was good with >80% agreement.

Results

Engagement - Interaction time

Overall, 22 visitor groups interacted with SynFlo 3.1 (concrete tangibles) and 20 groups interacted with SynFlo 3.2 (abstract tangibles), with a total of 89 users on both conditions. Visitors only interacted with one of the two prototypes. Table 1 summarizes the composition of user groups on each condition.

Table 1. Group type by condition

	SynFlo 3.1	SynFlo 3.2
One child	3	2
One child + adult	11	7
Two children	2	5
Two or three children + adult	3	4
Adults only	3	2
Total groups	22	20
Total adults	19 (age 20+)	16 (age 20+)
Total children	25 (avg age = 9.06; SD=3.25)	25 (avg age = 9.18; SD=3.58)

Using SynFlo 3.1, 21 out of 22 groups completed the protocol successfully - resulting in the E. coli changing color in the presence of a toxin (Figure 1). Using SynFlo 3.2, 18 out of 20 groups completed the protocol successfully. Groups spent significantly more time actively interacting with SynFlo 3.1 (concrete tangibles) with an average *active* interaction time of 3:58 (SD=1:37) and took significantly more time to complete the protocol successfully. Total time around the exhibit includes time spent waiting for the previous group to finish and is also significantly longer with SynFlo 3.1. Table 2 summarizes interaction times.

The differences in interaction times could be explained by our observation that with SynFlo 3.1 (concrete tangibles) some interactions were difficult to figure out and perform especially pouring (Figure 1: Step 3,4). With both prototypes, visitors had to figure out which tangibles to combine for the next phase of the protocol, but SynFlo 3.1 added the complexity of having to figure out a particular way to combine the tangibles. With SynFlo 3.1, the affordance of the tangibles would guide and limit this exploration. For example Fig. 4a shows two users exploring the gene tangible simultaneously using SynFlo 3.1; One discovers that the gene does not go into the toxin because the pieces do not allow it. The other discovers that the gene fits correctly into the plasmid's flask. SynFlo 3.2 on the other hand, does not constrain the configuration of cubes. Thus, visitors arranged and rearranged cubes flat on the table until a combination warranted a response (Figure 4b). It took SynFlo 3.1 users longer to figure how two pieces with concrete tangibles fit together than it did to neighbor all possible combinations of cubes with SynFlo 3.2.

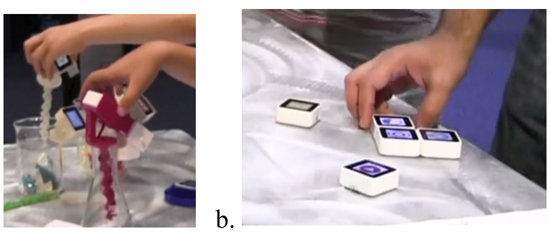
a. b.


Figure 4. Users explore how to combine tangibles with SynFlo 3.1 (a) and with SynFlo 3.2 (b)

Table 2: Interaction time by visitor group

Condition	SynFlo 3.1		SynFlo 3.2		
	N	M (SD)	N	M (SD)	*p*
Active interaction	22	3:58 (1:37)	20	2:24 (1:40)	.004*
Time to First Success	21	3:17 (1:14)	18	1:48 (1:00)	<.001*
Time to First Touch	22	1:40 (1:12)	19	1:39 (2:07)	.999
Total Time	22	7:27 (2:21)	20	5:48 (2:45)	.04*

Table 3: Age and attitude of child users

Condition	SynFlo 3.1 (concrete)		SynFlo 3.2 (abstract)		
	N	M (SD)	N	M (SD)	*p*
Age	25	9.06 (3.25)	29	9.17 (3.58)	.905
Difficulty	22	4.30 (2.63)	25	2.88 (1.71)	.03*
Enjoyment	22	8.41 (1.99)	24	8.13 (2.03)	.64

Enjoyment

Many users expressed enthusiasm about SynFlo. Responding to post task questions, users of SynFlo 3.1 (concrete tangibles) reported that on average the system was very enjoyable to use (8.41 on a scale of 10, SD=1.99, n=22). Users of SynFlo 3.2 also reported high enjoyment (8.13 on a scale of 10, SD=2.03, n=24). There was no significant difference between the two conditions.

Apprehendability

We looked at temporal and subjective measures as well as qualitative indicators to assess how apprehendable the exhibit was. First, we measured how much time it took users to initiate physical interaction with the exhibit from when they arrived. For this measure, we did not find a significant difference between the two prototypes (Table 2). When asking users to rate (on a scale of 10) how difficult it was to interact with the exhibit, users generally responded that the exhibit was not very difficult to figure out and interact with. However, users of SynFlo 3.1 (concrete tangibles) found it significantly more difficult to use (Table 3). As qualitative indicators we looked at verbal and physical adult interventions in mixed groups. We found that adults intervened more with SynFlo 3.1, (concrete tangibles) with 85.7% (12/14) of parents intervening (average of 5.92 SD=2.84 times per group), compared with SynFlo 3.2 with 72.7% (8/11) of parents intervening (average of 3.13 SD=2.47 times per group). Parent interventions came either in the form of physical assistance - pointing to a piece or performing the required actions, or in the form of verbal assistance - guiding and instructing the child. We speculate that the increase in parent involvement with SynFlo 3.1 is due not only to the fact that the children needed help to figure out the interactions, but also due to the use of concrete authentic tangibles (i.e. labware) that adults are familiar and comfortable with.

We also found that in both conditions, children visitors who observed another child interacting with the exhibit while waiting completed the protocol successfully in a shorter amount of time than the initial child (on average .75 minutes faster, n=7). This indicates that the visibility of objects and gestures facilitate some learning through observation.

Collaboration

In groups with parents and children, most adults watched and intervened when necessary. However, a few parent-child groups (4/25) interacted more like peers, figuring out the interaction together. In groups with two or more children, we identified several peer collaboration patterns with frequent role switching: working together - handing pieces, giving verbal instructions; working in parallel - side by side independent work; or, driver-navigator driver-passenger - one child takes over the interaction, leaving the other to give input or just watch. Children switched between these collaboration styles frequently using verbal and physical actions (e.g. taking away, sharing, pointing). Table 4 summarizes instances of peer collaboration.

All in all, we found more positive collaborative behavior (i.e. assisting and converging) among peers and more parent intervention with SynFlo 3.1, which with more challenging interaction created opportunities for collaboration.

Table 4. Average number of instances of peer collaboration

	SynFlo 3.1 (n=7)	SynFlo 3.2 (n=7)
Collaborative actions per group (assist physically, point to piece, verbal instructions, perform interaction together)	4.29 (SD=3.35)	3.29 (SD=2.50)
Diverging (grab or ask for piece)	1.38 (SD=1.85)	1.0 (SD=.71)

Learning

To assess learning we used several verbal and physical indicators. First, we conducted a discourse analysis of the dialogue around the exhibit. Visitors' content-related dialogue consisted of making observations and speculating about what happened, coordinating collaboration, and asking questions about context. We quantified the number of biology terms used and additional observations made without biology terms (Table 5). While no significant differences were found, the results indicate that both prototypes facilitated discussion of exhibit-related content and the use of relevant biology terminology.

Table 5. Dialogue analysis- Average utterances per group

	SynFlo 3.1		SynFlo 3.2	
	Children (n= 19)	Adults (n= 18)	Children (n= 17)	Adults (n= 12)
Uses biology term	1.42 (SD=2.01)	2.41 (SD=3.74)	2.56 (SD=3.01)	1.08 (SD=1.38)
Additional content-related	1.26 (SD=.93)	1.0 (SD=1.32)	1.56 (SD=.92)	.17 (SD=.58)

Upon completion, facilitators asked at least one child from each group questions (Table 6) that required them to reflect, focusing on either the function of the engineered bacteria (Q1) or the physical process of bio-design (Q2, Q3). Results (Table 6) indicate that children who interacted with SynFlo 3.1 had perhaps a better understanding of the function than those who interacted with SynFlo 3.2 and that users of both had a fair understanding of the process.

Table 6. Childrens' correct answers to post-task questions

	Question	SynFlo 3.1	SynFlo 3.2
Q1	Why did the bacteria turn X color but not Y color? (L4)	53.3% (8/15)	30.8% (4/13)
Q2	How did you get the gene into the bacteria? (L3)	60% (3/5)	60% (3/5)
Q3	What did the plasmid do? (L3)	33% (1/3)	71.4% (5/7)

Finally, in addition to the reflection prompted by the post task questions, we found some evidence of advanced inquiry and reflection during interaction. Several visitor groups experimented beyond the protocol, for example, with what would happen if they put multiple plasmids in the bacteria. Adults often asked the facilitators questions such as, "What's the principle behind all this?" or would try to connect the exhibit to prior knowledge, making comments such as "Genes are the building blocks of DNA, right?" A few children showed advanced understanding by making predictions, "So now the bacteria should sense the toxins".

DISCUSSION

We presented an evaluation in a museum of two versions of a novel interactive exhibit designed to expose visitors to complex concepts of biological engineering. We were particularly interested in how our design features, which include active tokens, concrete authentic tangibles, gestural interaction, multiple access points, and short play session, support the learning and design goals.

We found that the use of active tokens successfully bridged the time and size scales of biology to allow users to engage in an enjoyable and meaningful bio-design activity outside the wet laboratory (G1, G3). Almost all groups completed the bio-design protocol successfully, demonstrating basic understanding of abstraction and modularity in bio-design (G2, L1 and L2). The results of the dialogue analysis and visitors' responses to post task questions indicate that the exhibit facilitated understanding of the function of this bio-design activity (i.e. bio-sensing) (L4) and of the underlying scientific protocol (L3).

Gestural interaction with active tokens facilitated visible actions, which in turn supported learning through observation, parent intervention, and peer collaboration. Both prototypes provided multiple access points, supporting collaboration (Table 4). The duration of the play session (about 3 minutes) was sufficient for users to complete a bio-design protocol while also streamlining groups waiting around the exhibit. The use of concrete authentic labware (SynFlo 3.1) increased the difficulty of figuring out the interactions, which resulted in longer interaction time as well as in more parental engagement and peer collaboration (Table 4). Adults were more inclined to engage with the concrete tangibles, perhaps due to their familiarity with these real-world objects. The concrete tangibles also supported better understanding of the activity's context and purpose (Q1 Table 6).

Based on these findings, we suggest that combining gestural interaction with active tangible tokens can address the challenges of creating an interactive exhibit for bio-design including: bridging time and size scales, accommodating and streamlining diverse visitor groups, and facilitating complex interactivity with biological creations. Integrating *authentic* tangibles foster adult involvement and provide further context to the activity.

CONCLUSION AND FUTURE WORK

Biology is full of complexity, engaging phenomena, and personal relevance, making it a rich domain for open-ended play and exploration. We presented SynFlo, a tool that allows people to engage with biology by combining digital and tangible representations that simplify a bio design activity and provide room to tinker, and lessons learned about the benefits of gestural interaction with tangible active tokens for addressing the challenges of designing an interactive exhibit for bio-design. Future work will continue to tackle these challenges by expanding SynFlo to make room for creative thinking in bio-design, incorporating open-ended experimentation beyond set interactions, turning SynFlo into a tool for making with biology where complex interactivity can occur, emergent properties can arise, and creations can live or die depending on design.

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