Generation: A Novel Fabrication Game for Simulating Evolution and Natural Selection

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Figure 1: Overview of the game's components. *Generation* is a game that requires a 3D printer (left) to iteratively fabricate game pieces which the player uses to gradually assemble into more complex creatures (middle). The player takes a picture of their creature design (right), which is then analyzed by the game to simulate its survival in a dynamic digital ecosystem. The goal of the game is survival, and the player scores points for every evolutionary step they successfully take.

ABSTRACT

3D printers are becoming increasingly accessible to the average consumer, however their potential utility within games has yet to be fully explored. Integrating 3D printer fabrication technology within game design presents a novel means for engaging players and providing them with tangible representations of gameplay elements. This in turn could be employed to increase embodied gameplay and even embodied learning for the player. In this paper, we present a novel "fabrication game" designed to teach basic evolutionary concepts. In the game, players take turns physically assembling components 3D printed in real-time to iteratively evolve their creatures and observe the impact of their evolutionary choices on a digital population simulation. We discuss the potential of this game's unique design in leveraging real-time fabrication of tangibles to enhance a player's understanding of principles of evolution and natural selection.

CCS CONCEPTS

- **Applied computing** → **Interactive learning environments;**
- **Human-centered computing** → *Interactive systems and tools.*

KEYWORDS

3D printers, fabrication, tangibles, video game, educational game, simulation, evolution, natural selection

ACM Reference Format:

Katelyn M. Grasse and Edward F. Melcer. 2020. Generation: A Novel Fabrication Game for Simulating Evolution and Natural Selection. In *2020 Annual Symposium on Computer-Human Interaction in Play (CHI-PLAY '20 EA)*, November 2–4, 2020, Virtual Event, Canada. ACM, New York, NY, USA, 5 pages. <https://doi.org/10.1145/3383668.3419859>

1 INTRODUCTION

Fabrication technologies such as 3D printers are becoming increasingly accessible to the general public chiefly because the equipment is becoming smaller, cheaper and easier to operate. As a result, people have begun to explore incorporation of 3D printers into game design, coining terms like fabrication games or playful fabrication [6, 31]. However, current fabrication games typically focus on utilizing 3D printers to generate pieces in advance for use in analog games, e.g., [6], rather than leveraging the real-time fabrication capabilities of such tools directly into the gameplay.

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CHI-PLAY '20 EA, November 2–4, 2020, Virtual Event, Canada

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ACM ISBN 978-1-4503-7587-0/20/11.

<https://doi.org/10.1145/3383668.3419859>

Tangibles are a powerful tool for engaging users [12], providing customized physical objects and interactions that deliver a more intuitive, embodied experience [3, 5, 13]. Notably, within the context of games, the embodied interactions that tangibles afford can even be applied to enhance player experience and learning outcomes [18, 19, 22]. However, we posit that the real-time capabilities of fabrication technologies used to create tangibles (such as 3D printers) have not been fully explored within the context of games and learning. For instance, while there are examples of 3D printers being used to supplement teaching methods for topics like math, geometry or engineering, cases involving games are currently rare [15, 17, 26]. In this interactivity paper, we present our initial exploration into expanding the design space of fabrication games to leverage the real-time fabrication capabilities of 3D printers. This is done through the creation of our own educational fabrication game for teaching concepts related to evolution and natural selection, titled *Generation*. In the following sections, we will discuss the design rationale for *Generation*, as well as the potential of this game's unique design in leveraging real-time fabrication of tangibles to enhance a player's understanding of principles of evolution and natural selection.

2 BACKGROUND

2.1 Fabrication Technologies and Games

Fabrication technology enables digital problems to be manifested in the real world to allow for less constrained and more intuitive and creative manipulation [24, 33]. As a result, various fabrication technologies have been investigated to facilitate exploratory play and problem solving, including mediums such as textiles, beading and scrapbooking [30]. These modes of crafting have been successfully employed to enhance playful interactivity in games or education, but rarely both together [1, 7]. *BeadED Adventures* [28] and the *eBee* electronic quilting project [8, 21] are exemplars of the merge of crafting, gaming and STEM education, both of which utilize the affordances of their chosen craft materials to facilitate interest in and understanding of the educational topics of interest [29]. In this paper, we seek to extend the scope of hybridized (physical-digital) fabrication games designed for learning by combining a novel educational video game with 3D printer technology.

2.2 Embodied Educational Game Design

Integrating fabrication technology, namely 3D printers, into video games provides a novel opportunity for creating tangibles that can support embodied game design and learning [6]. While there are various techniques to incorporate embodiment into games, such as through AR or VR, the use of tangibles and tangible interactions for embodied game design is one of the most popular approaches [19]. Notably, tangibles can embody (learning) concepts in two distinct ways: 1) through the use of embodied metaphors and interactions with the physical artifacts themselves [4], and 2) through the shape of the artifact itself and how that represents the learning concepts [13, 23]. As a result, their benefits to learning have been hypothesized and studied broadly [16, 22]. For instance, incorporating tangibles and principles of embodiment into learning activities has been shown to elicit boosts to engagement, spatial recall and mental manipulation, intuition for physical interactions and mappings, and

positive feelings towards learning science content [18]. There have been a number of embodied educational games that utilize tangibles to teach a variety of topics such as programming [10, 19, 33], music [4, 5], reading and spelling [9], anatomy [25], and animal foraging behavior [11]. *Generation* is similarly designed to take advantage of the embodied affordances that tangibles provide in order to make learning about natural evolution more engaging, intuitive and fun.

2.3 Evolution Education

Evolution is recognized as the unifying scientific theory in biology, but teaching this topic is notably difficult [2, 27]. Both digital and physical games have been extensively studied as a means for making learning about evolutionary concepts easier and more intuitive [11, 14, 20]. Examples of digital entertainment games that feature principles of evolution include *SimLife* (1992), *Spore* (2008), *Niche* (2016) and *Ecosystem* (2020 expected release). Examples of explicitly educational games include the *Evolution Board Game* (2019) and *Catch a Mimic: Natural Selection* (2019), the latter of which can be played in virtual reality (VR) to encourage embodied learning. Game designers emphasize various evolutionary principles at complexity levels that are most relevant to the goals of play. However, one major feature that these games share is that they demonstrate how species can change over the course of many generations to adapt to a changing environment – the core principle of evolutionary theory. *Generation* will also help players develop a better understanding of this principle by challenging them to design progressively more complex creatures in order to survive in a dynamic ecosystem.

3 DESIGN AND GAMEPLAY

Generation is a game designed to help teach principles of evolution. A variety of core evolutionary concepts can emerge while playing the game, including 1) natural selection, 2) random mutation, 3) common descent, and 4) that species change gradually over the course of many generations. Evolution is a process that involves both rules (e.g., survival of the fittest) and randomness (e.g., genetic mutations), therefore both elements were incorporated into the game's design through the turn-based construction (i.e., evolution) of tangible creatures. Just as it is for creatures in the natural world, the major goal of the game is to survive for as long as possible by adapting to unexpected challenges. Players of this game will learn to consider how every decision could affect the stability of the rest of the ecosystem, as well as ways in which any changes will in turn affect future survivability.

3.1 Game Design Overview

This fabrication game combines a digital simulation with physical gameplay to afford the player a novel physically engaging experience for learning about evolution. Though we expect the game can be designed for multiple players in a cooperative or competitive format, a single-player game playing with the computer is considered first for simplicity. At the start of the game, the player is provided a single printed game piece representing one member of a homogeneous population of simple organisms. Players of the game should be able to recognize that this starting creature is the single common ancestor from which all future species will descend. The

game is turn-based, where player and computer alternate printing new shapes to iteratively assemble into their increasingly complex creature designs. A camera connected to the game analyzes an image of the player creature's physical design to measure its attributes, wherein features like the number or arrangement of the connected shapes are used to determine the creature's attack, defense, speed and stamina. These attributes are then fed into an algorithm that simulates the creature's population size dynamics, which affect and are affected by the rest of the ecosystem. The other simulated species in the ecosystem will also periodically change in an attempt to improve their own survivability. The player alternates between changing their creature and observing the effects of their design choices upon the gradually changing ecosystem. The ultimate objective of the game is to survive as long as possible (see How to Beat the Game for more details).

3.2 Creature Design

Players design creatures by connecting together a collection of up to four types of printed game pieces. These pieces are designed for simplicity to minimize fabrication times (see Figure 1). Each type of game piece is a regular polygon (meaning they are equiangular and equilateral), and every piece has equal length sides – therefore, for example, one hexagon takes up the same area as six triangles. Pieces are distinguished by both their shape and color for visual clarity, including red triangles, yellow squares, green pentagons and blue hexagons.

The player decides when to print a new piece, but the game restricts which shape may be printed (players choose between two random options each turn). By restricting the gameplay rules in this way, players are not able to plan out the creature's design at the start of the game, but they can determine the rate at which it evolves and maintain some authority over its composition. Each piece has a limited number of sides, and so is limited in the number of pieces to which it can be attached. As soon as a new piece is printed, the player must integrate it into the creature's design while following one simple rule: every piece must always have at least two sides free. For example, triangles can only be attached to one other shape, whereas hexagons can be attached to up to four shapes. As stated before, the arrangement of the game pieces determine the creature's various attributes:

- (1) **Attack** is equal to the number of red triangles.
- (2) **Defense** is equal to the number of blue hexagons. A creature becomes the prey of another creature if the prey's defense is lower than the predator's attack.
- (3) **Speed** is calculated by finding the creature's maximum length and dividing it by the creature's average width along the orthogonal axis. As a result, long and skinny creatures are fast compared to rounder ones.
- (4) **Stamina** is inversely related to the amount of kinetic energy required to move. We chose to define a creature's kinetic energy by multiplying the cube of its size by the square of its speed. Size is equivalent to the combined area of the creature's shapes. Faster and larger creatures expend more energy to travel a certain distance. As a result, predators with lower kinetic energy have higher stamina and are better able to catch prey.

Figure 2: Examples of evolution of creature designs and population size simulation. (A) Players take turns printing individual game pieces to assemble into progressively more complex creatures. The computer also chooses designs that favor survivability. (B) Lotka-Volterra equations can be used to simulate predator and prey population sizes over time. Changes in either creature's attributes cause changes in both creature's population dynamics. The game terminates when only one creature population remains.

3.3 Population Simulation

A series of coupled ordinary differential equations can be used to model the population dynamics of each of the species in an ecosystem. A classic simple example of such a system would involve two organisms, and their population size dynamics can be described by a pair of Lotka-Volterra equations [32]. These equations (1, 2) can be used to model the time-dependent rates of change (d/dt) of the sizes of populations of prey (N) and predator (P), where (r) is the prey birth rate, (a) is the prey death rate, (b) is the predator birth rate, and (m) is the predator death rate.

$$\frac{dN}{dt} = rN - aNP \quad (1) \quad \frac{dP}{dt} = bNP - mP \quad (2)$$

The four creature attribute variables described in the previous section can be used to determine the prey death rate (a) – often defined to be equivalent to the predation rate – for every predator-prey relationship in the ecosystem. This relationship could resemble the following example (3):

$$a = \frac{\frac{P_{att}-N_{def}}{P_{att}} + \frac{P_{spe}-N_{spe}}{P_{spe}} + \frac{P_{sta}-N_{sta}}{P_{sta}}}{3} - \frac{N_{att} - P_{def}}{N_{att}} \quad (3)$$

In this case, all four attributes from both creatures are utilized to determine the predator's rate of success. When the initial conditions and the values of the constants (r , a , b , m) are balanced, the equations reveal co-dependent oscillatory changes in the size of each species' population that are stable over time (Figure 2B). While these equations are only an ideal approximation for modeling population dynamics that occur in reality, they nonetheless can provide the player with a basic understanding of the instability of species' rates of survival over time.

3.4 How to Beat the Game

Natural organisms do not evolve in order to reach some ultimate form, and similarly it is not possible to "beat" this game. Instead, players earn points for every evolutionary step they take, and the goal is to earn as many points as possible. In other words, the main objective of this game is to survive for as long as possible. To do so, the player must not allow their creature's population to fall below a certain size. This rule should be easy for players to understand at a glance – when the population shrinks too small, its members will not be able to procreate as easily (or at all), leading to their extinction. Maintaining a respectable population size is an intuitive survival goal, but the player can also lose the game if they become the only organism left in the ecosystem, meaning that all other species have died off. This outcome is the equivalent of a mass extinction event, where the stability of the entire ecosystem has collapsed. When mass extinctions occur in nature, higher-order organisms are the most vulnerable because they are most likely to lose access to stable sources of food, leading to their extinction. Using these rules, the game will encourage players to avoid making creatures that are overly powerful with respect to their environment. Instead, the game will challenge players to explore designs that enable their creature to continue living in harmony with nature.

4 DISCUSSION

In this paper, we have presented a prototype version of *Generation*, a novel fabrication game that utilizes 3D printer technology and embodied play to teach principles of evolution. While there is prior work exploring 1) the use of 3D printers for enhancing gameplay and 2) crafting games for educational purposes, this game expands the scope of fabrication games by merging the two domains. Furthermore, in comparison to games which fabricate game pieces prior to play or in-between play sessions, this game leverages the 3D printer's real-time fabrication to afford the player access to new pieces throughout the game. The current prototype pieces each require 1-3 minutes to print, but cutting all print times down to less than a minute is feasible through a redesign of current game pieces to be more efficient for printing (i.e., smaller pieces, less infill, larger layer heights, and so forth). We also note that the time required

to print these pieces will also naturally decrease as 3D printers continue to improve in speed and accuracy over the coming years.

4.1 Educational Design and Goals

The rules of the game were designed to make a variety of important evolutionary concepts accessible to any player. For example, players will learn about common descent by witnessing multiple lineages of creatures that evolve from the same simple organism diverge drastically throughout the game. Furthermore, the incremental competition between species will expose how natural selection is only possible when minor shifts in creature design occur gradually over time. Finally, an element of luck will demonstrate that species evolve new traits in a random fashion and develop survival advantages as a result of natural selection rather than through purposeful intent.

4.2 Target Player Experience

This game is still under development, but we expect future players to feel engaged and immersed when physically interacting with their creatures, especially compared to a hypothetical case where a computer program is used instead to execute creature design. Requiring use of a 3D printer to generate game pieces will add an element of idleness and reflection to the game, which should encourage players to think carefully about the advantages and disadvantages of their design choices. Additionally, the randomness built into this game will mean that every playthrough will be unique, therefore those who choose to play the game multiple times will likely learn something new each time. Furthermore, the presence of this relatively new technology should inspire players' general wonder and interest in STEM, and enabling access to an unlimited number of pieces means players can easily keep their creatures as trophies. The physical interactivity afforded by this game will create opportunities for embodied learning, which will likely help boost positive feelings towards learning about evolution. Ultimately, by designing creatures in physical space, players should develop richer intuition and memories about their learning experience.

4.3 Future Directions

Future iterations of this game will explore incorporating game mechanics that more realistically model evolutionary forces, including environmental pressures (e.g., evolving in a mountainous area penalizes speed) and more complex ecosystems (e.g., carrying capacities and multiple tiers of predators). To further increase engagement, a projector and location tracking system could be implemented to enable players to test their creature designs in physical space. Furthermore, in order to explore the benefits of creating tangibles in real-time on learning outcomes, we plan to conduct studies comparing use of the current system with one that is entirely digital.

ACKNOWLEDGMENTS

The authors would like to thank Dane Grasse, Ethan Osborne, Max Cronce and Vivian Pham for their valuable feedback on the game design and manuscript. This research was supported in part by a Faculty Research Grant awarded by the Committee on Research from the University of California, Santa Cruz.

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