# BacToMars: Creative Engagement with Bio-Design for Children

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## Abstract

We present BacToMars, an educational video game that engages elementary school children in a bio-design activity. We describe its design and implementation, and discuss design considerations for developing playful and developmentally-appropriate interactive activities, which enable children to grasp complex scientific concepts and apply bio-design to solve problems. We share results from preliminary evaluation, and describe next steps in our investigation.

## Author Keywords

Play; children; bio-design; educational games.

## ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces---theory and methods

## Introduction

In today's world, biology has become a powerful technology, advancing innovation in domains ranging from food shortage, to clean water, and space travel. It is therefore important to inspire future innovators to solve problems at the intersection of science and technology by exposing them to the burgeoning fields of biological engineering and bio-design. However, the elementary natural science curriculum does not include emerging domains of knowledge like biological engineering that cut across disciplinary boundaries [1].

There is a lack of concrete tools that expose children to abstract scientific concepts such as traits, cells, genes, and the conceptual framework of biological engineering.

In this paper, we present the design, implementation, and preliminary evaluation of a novel educational video game called BacToMars, which is designed to encourage students in elementary school to explore abstract scientific concepts in concrete ways. The design of BacToMars is inspired by the interactive museum exhibit BacPack for New Frontiers [7]. However, it is designed for formal learning in elementary school class settings. Following, we describe the design and implementation of BacToMars. We also share results from preliminary evaluations and discuss design considerations for the development of an engaging educational game for bio-design.

## Related Work
Our design of BacToMars draws upon Papert's Constructionist educational framework [10] and previous work that explores how children learn through hands-on technology-rich activities [3, 4]. When applied to learning in biological engineering, Constructionism means that learners construct knowledge by solving real-world problems using a toolkit of biological parts [7, 9]. BacToMars was also designed to foster two core aspects of computational thinking [11]: abstraction and modularity [5].

A number of video games have been developed to engage players in the design of new organisms (e.g. Spore, Cubivore, Graffiti Kingdom) or objects (e.g. Particles!). However, these games do not provide a platform for children to participate in creative problem-solving through bio-design. e.pixel [2] and TrapIt![6]

are interactive museum exhibits that allow young audiences to observe live bacterial cells. SynFlo [9] and BacPack for New Frontiers [7] engage children in problem-solving using biological design. These exhibits inspired our work but they target informal museum settings, which are inherently different from formal learning in elementary classroom settings. For example, BacToMars supports extended engagement and contains levels to support progression, as well as a help system to imitate an expert facilitator.

## Application Domain and Design Goals
*Biological Engineering*
Biological engineering aims to provide creative solutions to a wide range of real-world problems. It applies the principles of standardization, abstraction, and modularity to the design of living organisms with new properties. In this game, genetic programs are composed from standardized biological parts called BioBricks, which are used like "Lego Bricks" to compose programs with complex behaviors.

The premise of the game draws upon a widely-known research paper about the utility of bio-design techniques for manned exploration missions to Mars [8]. The authors propose to identify which molecules could be utilized to create desired products. Similar to the exhibit BacPack for New Frontiers [7], BacToMars mirrors this investigation by allowing children to experiment with biological designs of bacteria that consume input materials and produce desired output materials essential for sustaining a mission to Mars.

*Learning and Design Goals*
Based on the BacPack exhibit [7] but focusing on formal learning settings, we have identified specific and

Figure 1: The first level of BacToMars. In this level, children are only allowed to make oxygen.
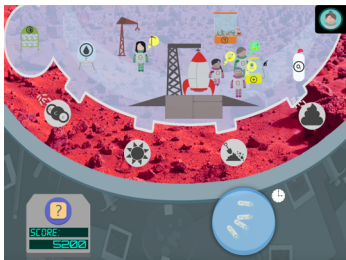


Figure 2: The fourth level of BacToMars. Players may use all five resources to create all six products. The goal of this level is to build the launch pad and rocket so the astronauts can escape Mars.

measurable learning goals for BacToMars that can be taught to elementary school students (2nd-5th grade) in a developmentally-appropriate way: (L1) Introduce basic concepts of genetics, with a focus on what genes and DNA are; (L2) Facilitate the design of genetic programs that include input and output, and where output from one program could serve as input to a different program; (L3) Introduce the foundations of biological engineering: using methods to build things that solve real-world problems, and following a concrete process; (L4) demonstrate the principles of abstraction and modularity—genes with documented functionality are used as standard biological parts, and are combined to create new biological systems; and (L5) Engage players in creative problem-solving of critical challenges related to survival on Mars. Our design goals for BacToMars were informed by these learning goals and influenced by a constructivist educational philosophy: G1) Facilitate the development of inquiry skills through a hands-on playful experience and creative problem-solving; G2) Provide scaffolding, help, feedback, and guidance within the game; and G3) Provide opportunities for collaborative learning.

## Design Iterations and Rationale

The premise of BacToMars is that players take on the role of a scientist-astronaut who is helping a team of astronauts. The astronauts settle on Mars and build a bio-dome; however, their supplies are destroyed by a dust storm. The player is challenged to work with a biological engineer character to solve the real-world problem of survival on Mars by designing bacteria that can help the astronauts. The bacteria consume resources that exist on Mars (e.g. soil, $CO_2$, biomass) and produce products that are required for sustaining human life on Mars (e.g. water, nutrients, $O_2$). At the

start of the game, players are introduced to the Mars team and treated as a member of the team. Before playing the game, players watch three brief introductory videos that explain the goal of the game and introduce key concepts, such as the environment on Earth and on Mars, natural resources, genetics, and bio-design. Simple language and animations are used to explain these concepts in an appropriate manner while maintaining scientific accuracy. Next, the bioengineer character guides the player in designing bacteria that consume available resources and produce essential products.

The game space is divided into two areas: a wet lab (on Mars) with a workbench station, and the Mars landscape, which includes a bio-dome where astronauts carry necessary building products to the ship they are constructing and consume essential life-support products (see Figures 1 and 2). Included in the wet lab area is a score to reflect the player's overall state, and a button to trigger a scaffolding animation.

Players use eleven representations of BioBricks (i.e. genes) to design and engineer the bacteria that make essential products. The quantity of products in the biodome is gradually reduced over time. Players are required to pick two genes: an input gene that consumes a particular resource and an output gene that produces a product. These two genes are combined into a genetic program. Some combinations of input and output genes are more effective than others. Figure 3 shows some of the possible combinations. In advanced levels, players can use biomass as both a resource and a product.
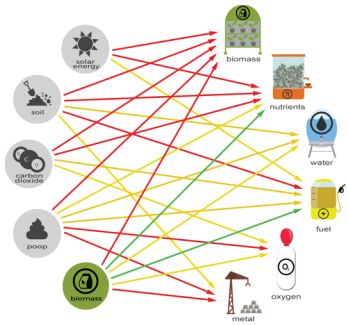
Figure 3: Subset of possible resource and product combinations, color coded based on how many units are produced by each combination: green = 3 units, yellow = 2 units, red = 1 unit. Green combinations are most efficient.



Figure 4: Preliminary testing of BacToMars with children. The two children pictured chose to play the game collaboratively without being prompted to do so.

Players then insert the genetic program into a digital plasmid (i.e. ring of DNA) and add the plasmid to a bacterial cell, which results in the growth of a colony of bacteria containing the genetic program. The players release the bacteria to Mars by dragging the petri dish with the colony towards the resource on the Martian landscape (see Figure 2). The bacteria gather around the resources they consume and produce a product, which is added to the products available in the bio-dome. The astronaut figures move around the bio-dome, providing feedback to users and indicating what products are running low, as well as picking up the products players create and consuming them or carrying them to where they are needed.

*Implementation*
BacToMars was created in JavaScript using the Phaser.IO game engine. It is optimized for Chrome on a laptop, but future iterations will focus on tablets. The current prototype implements six levels. We are currently developing additional levels as well as support for multi-player.

*Design Rationale*
We encountered several challenges in the design of BacToMars. Here we describe the design choices we made to address them. Many are applicable to games beyond the scope of a formal elementary classroom setting. Our choices were informed by user and expert feedback we received through our iterative design process as well as by frameworks for learning with technology-rich experiences [3, 4].

Overcoming time and size scales – This is a known challenge in the design of educational bio-design activities [7, 9]. In the game, animation bridges the time scale of bio-design from days to seconds through simulation, with the concept of time represented by an animated clock face. To represent genes, we draw upon the metaphor of BioBricks, which is widely used within bio-design [8], and embody two important engineering principles: abstraction and modularity. We use a jigsaw puzzle metaphor to indicate whether genes are considered input (consuming resources) or output (producing products). Animation is used to communicate size scale, showing that a genetic program composed of two genes fits within a plasmid that is then inserted into a bacterial cell.

Supporting a young audience – The game uses simple graphics with minimal text. Various features are used to provide built-in scaffolds to guide players, such as introductory animation videos, tips, a demonstration of a virtual hand showing players what to tap and where to drag, a companion bioengineer character that provides guidance, and a help button.

Fostering creative problem solving – In early levels of the game, we provide players with a limited number of genes and with contextual hints indicating how and which necessities to produce. In intermediate levels, players are provided with up to 11 different genes and are guided by a dynamic simulation of resource depletion and production. At these levels, players are required to consider which combinations of genes are most effective and to prioritize and plan their utilization of resources. In advanced levels, players are able to identify new genes that could be helpful and to invent new combinations of genes to improve the lives of the astronauts on Mars. At these levels, players are encouraged to apply their creativity and to experiment with new ideas for bio-design.

Supporting collaborative learning – BacToMars will support teams of up to four simultaneous players that will work in parallel on different biological designs. The engineered bacteria are released to a common environment (i.e. Mars landscape) so that all team members can observe the impact. Players are encouraged to collaborate on solving important problems (e.g. lack of oxygen, need for lighting a particular area) as well as to draw upon the bio-designs (i.e. genetic programs) of fellow team members. We intend for the game to be played in a co-located collaborative settings - children seated next to each other each with their own tablet, so that players can communicate directly while collaborating.

## Preliminary Evaluation

Our preliminary evaluation focused on the learnability of the game, learning of core terminology and concepts, and the level of engagement.

Early pilot-testing with two children in second and third grade indicated that the children had trouble understanding the overall goal of the game and figuring out game mechanics. To address these issues, we introduced the scaffolding mechanisms discussed above and developed introductory animation videos. We evaluated the videos with elementary school teachers and child development specialists and iterated on the videos' content and design to ensure that they were developmentally appropriate.

Pilot-studies of the current version of BacToMars and videos (with $N$=7 elementary school students; males=5 and females=2; 1st graders=1, 2nd graders=3, 3rd graders=2, 5th graders=1) show that players were engaged with the game and enjoyed the play session.

During these trials, children first completed a pre-survey targeting their prior knowledge regarding core biological engineering concepts and terminology. For the 1st grader participant, the questions were read aloud. Next, children watched the three animated videos. After the videos, they were prompted to play the BackToMars game for 15 minutes. During this time, the researchers gave minimal prompts or help to the children. After 15 minutes, children were allowed to continue playing for up to 25 minutes before moving on to the post-task questionnaire to assess learning of core concepts and terminology. Finally, a researcher conducted a debrief with each participant.

Results show that all children were able to successfully engage in gameplay. Participants reiterated that the videos were a necessary addition to the game. In the words of one child, "I really thought the video was giving me a lot." In Level 4, where a new concept is introduced, we observed some confusion, yet none of the participant used the help button. Future iterations will highlight the option and introduce contextual tips. The mean play time was 19.89 minutes (STD=3.40 minutes) with only one child choosing not to extend their play time. While playing, children made comments (mostly to themselves but sometime to another player sitting close by) like "They thirsty they want water" and "I am making so much oxygen…". When children played next to each other they sometimes collaborated. For example, one child commented "They hungry", and the other child suggested "Use nutrients and sun". We interpret these comments as indicators of engagement.

Pre- and post- assessments revealed that the videos and game were generally successful at teaching some core concepts. However, older participants

demonstrated greater levels of learning than younger participants, suggesting elements need refinement to make the content domain developmentally-appropriate for a young audience. In the post-test debrief and surveys, all children shared overall enjoyment. When asked about favorite aspects of the game one 3rd grader commented "I liked how the pictures help you figure out what they [astronauts] need", another 2nd grader said "trying to find out the combinations that you need to do," a 5th grader mentioned "I liked how there would be a mixture of different things that you'd need to make, so I'd keep testing and trying to make enough." These comments indicate that our design indeed prompted inquiry and problem solving.

## Conclusions and Future Work

We presented the design, implementation, and preliminary evaluation of BacToMars, an educational video game that engages elementary school children in problem-solving through bio-design. BacToMars acts as a medium for children to experiment with the emerging field of biological engineering without costly equipment and the long wait-times inherent to a wet lab setting. We will continue to refine BacToMars through an iterative and participatory process. We plan to deploy the game with an accompanying curriculum in schools Fall 2017 and use it to further investigate how games can fit into a lesson plan, as well as what abstract scientific and engineering concepts young children are capable of learning when provided with engaging and developmentally-appropriate interactive experiences.

## Acknowledgements

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