Executive Summary: Design of a Puzzle Box for the Reber Building Escape Room to encourage students to pursue STEM

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This document presents our team's puzzle box design. Our puzzle box, which focuses on science, technology, engineering, and math (STEM) based principles, will work to solve the educational need of the lack of STEM enrollment throughout Penn State. This is shown as a problem throughout the Unites States as only 23% of students in higher education are enrolled in STEM programs. [1] Our puzzle box could be a solution to this problem by encouraging young students to pursue careers in STEM through mechanisms that apply STEM.

There are specific needs for the prototype design, which includes user experience, durability, ease of use, and aesthetics. The most important need is for the user to have an enjoyable, learning, and engaging experience through the mechanisms in the box. The team's goal is the inspire the user to explore many the options of STEM so that they find the path that is best for them. The need for a durable box is so that the puzzle box can survive a drop from waist height. If it was resting on a table and got bumped off, or if it slipped from the user's hands, it needs to be able to survive that so that it can function effectively for many years. Our team considered ease of use as a customer need by sanding down sharp edges. It was important for the team to also make sure no edges of the acrylic were extruded and that the box was small and lightweight. Another important customer need is aesthetics. Having a nice-looking puzzle box will benefit the escape room, along with encourage interest from the user. This was applied along with our corresponding metrics to get our target values for our metrics. Once the team had our metric values, we needed to start generating some concepts. The concept generation, screening, and selection will be covered in the first part of the executive summary. Later, the sequence of prototypes as well as the final design will be discussed further.

Concept Generation, Screening, and Selection

The most important need for the team is user experience. It is important for the team to apply STEM principles from a variety of fields that tie into mechanical engineering. The team came up with possible design aspects through the 6-3-5 method during lab. The proposed designs considered by the team include: magnetic or slide lid, a ball and maze, circuit, and a solenoid or spring latch.

For the team to reduce the number of concepts, a screening and scoring matrix was used. Concepts were screened with "+" for positive scores and "-" for a negative score against the customer needs in order to choose concepts our team felt were most important. The outcomes were then combined and altered by the team. A scoring matrix was used to rank the designs one last time. Based on the matrices, the lid was determined to have a magnetic latch. The team feels that the magnet will be easiest to conceal and is more STEM related, drawing principles from the Physics 212 course all engineering have to take. The second mechanism that was chosen from the screening was the ball and maze. The ball, once maneuvered through the maze, will drop into the hole and conduct a current to complete the circuit. The concepts of a maze use rolling and friction properties discussed by early physics and mechanics classes. The maze is based off a popular TV show called, "Westworld," to connect lab and research with engineering. Since we a using a circuit, the team determined through the matrixes that it was best to use a solenoid latch. The solenoid and help the user understand how magnetism and electricity are related, deriving principles from electrical engineering. As a team, we felt this was important because mechanical engineers can design products but do not normally see the electrical control through. This will help create a better understanding of how all the engineering majors are connected and provide thought on an alternate route in STEM if mechanical engineering does not work out. The next step our team took was constructing our prototypes.

Sequence of Protypes

The sequence of protypes for this project were designed by the team and consist of the zeroth, alpha 1, alpha 2, and beta prototypes. This allowed for the team to see the build progress and make any necessary adaptations as the time progressed.

For the zeroth prototype, the team constructed the box using cardboard and basic crafting materials such as fridge magnets, glue, pipe cleaners, and construction paper. This design helped our team adjust future designs after seeing how the placement and mechanisms aligned. We decided to have the magnetic lid have a lip instead of being flush with the walls as shown below in **Figure 1**. This will prevent the load from being an obvious mechanism to the user. When purchasing magnets to use, the team found strong brick magnets and reoriented the design shown in **Figure 1** below.

The alpha 1 prototype frame was constructed to have the lip design. This new design concealed the hidden lid as we expected, making the box look more aesthetic in the process. For our maze design we realized, based on new lip design, that we needed to make it smaller than expected to fit inside the box. The maze that was printed for this prototype was not used in the final design. The sizes of the electrical components used were measured out on cardboard and placed in possible locations. This help the team determine final placements of the mechanisms.

From alpha 1 to the alpha 2, shown below (c), our team was able to sand down the wood using different grits of sandpaper. The team then stained the wood using a golden oak finish to add a rustic look to the box for a more aesthetic design. After the multiple coats of stain dried, coats of polyurethane were added to protect the wood. The team reprinted a smaller maze that could fit inside the box. We placed the maze on a wooden platform and drilled a hole through it to allow the metal ball to complete the circuit underneath. The electric components we ordered arrived and we placed them in the box unprogrammed. Following the alpha 2 prototype we began to work on the beta prototype and final design.

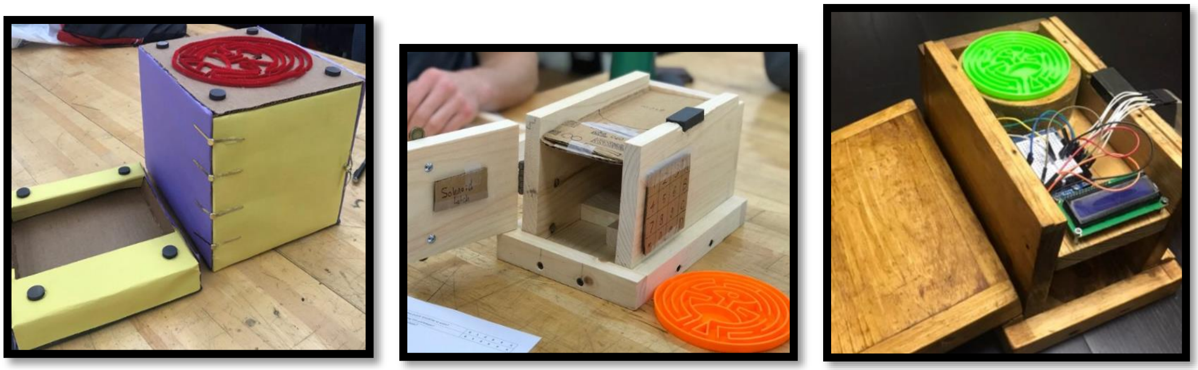

Figure 1. Sequence of prototypes for the puzzle box: (left) zeroth prototype, (middle) alpha 1 prototype, and (right) alpha 2 prototype

The team's beta prototype included a couple improvements from the previous iterations. Trim was sanded, stained, and coated with polyurethane, before being added to the edges of the box. This adds another level of aesthetics to the design as it conceals the hidden magnet more. The team also used a laser cutter in the Learning Factory to cut a piece of acrylic to use to cover the maze. Loose wires were soldered and cleaned up. New 9V batteries were purchased to power the microcontroller and relay effectively, the old battery could not do either. Brackets and components were screwed down into their final positions and a machined bracket made on a mill in the Learning Factory is used underneath the electrical control board in order to create a circuit for the ball bearing balls to complete.

Figure 2. Beta Prototype, inside view

Performance and Final Design

In order to see that the puzzle box satisfies the metrics and specifications, our team analyzed the performance of the beta prototype. The number of our mechanisms is four, which is beyond our expectation in the proposal that we stated our puzzle have three main mechanisms. More deeply to analyzed, all four mechanism are STEM-related, which are magnet lid, maze, digital lock, and the combination lock. The purpose of our puzzle box and main customer need is to inspire prospective engineers into the STEM field, and our puzzle box had high achievement rate on this application. The time to solve our puzzle box is another significant aspect to rate our puzzle box's performance. The intended use of the puzzle box is to be used in the escape room, it is important to note that this should not take too much time to solve that it. As a team we felt that we want a box that should take less than 10 minutes to solve. The team tested the puzzle box different groups of people with different education degrees. The team asked a group of kinesiology students, business students, and engineering students to solve the box. The difficulty of our beta prototype reaches our target goal as the average time to solve the box was around five minutes. This time can be adjusted electronically as well. Delays is sequences can be programmed in to punish guessing to add to the time to solve. Additionally, about the durability, our prototype is self- supporting and can survive a fall from a waist high drop. The frame itself was tested for this metric and help up to the test. Our puzzle box is supposed to place on a large flat table and does not need lifting during the solving process, so it would most likely not be lifted over a foot high. Hence, the durability of our beta prototype is acceptable. We had old-fashion style handle and hinge on our beta prototype and coated the whole box with stain and polyurethane. From the aesthetic perspective, our prototype is pleasing and attractive to our users which would raise users' experience. All the edges are sanded and the size is right enough to be handle by at least a single person. We consider our puzzle box to be user friendly and safe to use.

Next, our puzzle box was weighted against the requirements of the class. User experience, durability, and aesthetic were all explained in the previous paragraph. A new metric, effort and originality, is introduced. The team designed a box that is original when compared to other boxes in the class as well as online. The box is smaller in size, making it comparable to one other box in the class. Though other groups used mazes in their designs, our team implemented it aesthetically by design, as well functionally, as it is used to complete a circuit. The most unique aspect of the box is the Arduino microcontroller used to control a keypad and solenoid as no other groups used this and the level of difficulty required more effort to implement. The effort of the box can be easily seen in the outside aesthetics. Days were put into sanding, staining, drying, and repeated in order to give the box its unique rustic look. On top of that, a couple days of applying polyurethane and drying were required as well. Many more hours were put into a SolidWorks model of the box as well as frame assembly. Given the design constraints, our puzzle box satisfies these as well. The box includes two 3D printed parts as well as a machined part. Design constraint 4, no tape being allowed anywhere on the project, was overridden by our team for safety reasons. There are only a couple spots in the project that use tape, and these spots are the soldered parts of wires so that the risk of fire is reduced. No major components or pieces of this box use tape outside of a couple wires.

The improvements we are going to add on final design is wire arrangement and easy understanding math hints through a combination lock. The wires are not well-arranged on our beta prototype. The disordered wire can be easily accessed by users so that it is highly possibly to be undone. The open wire would lead to safety problem as well, so we will wrap possible connections with electrical tape in our final design.

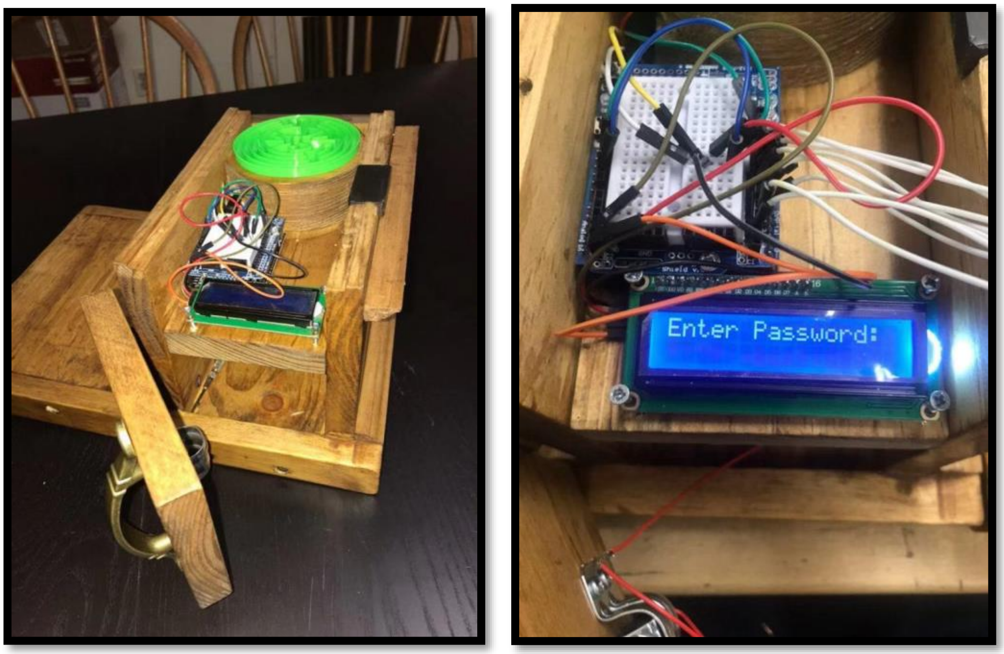

Figure 3. Our beta prototype with (left) full view of our puzzle box and (right) the wiring in the box

Appendix A: Background on the Design Team

This appendix presents background of the design team that created this puzzle box. Shown in Figure A-1 below, is a picture of the design team with their puzzle box.

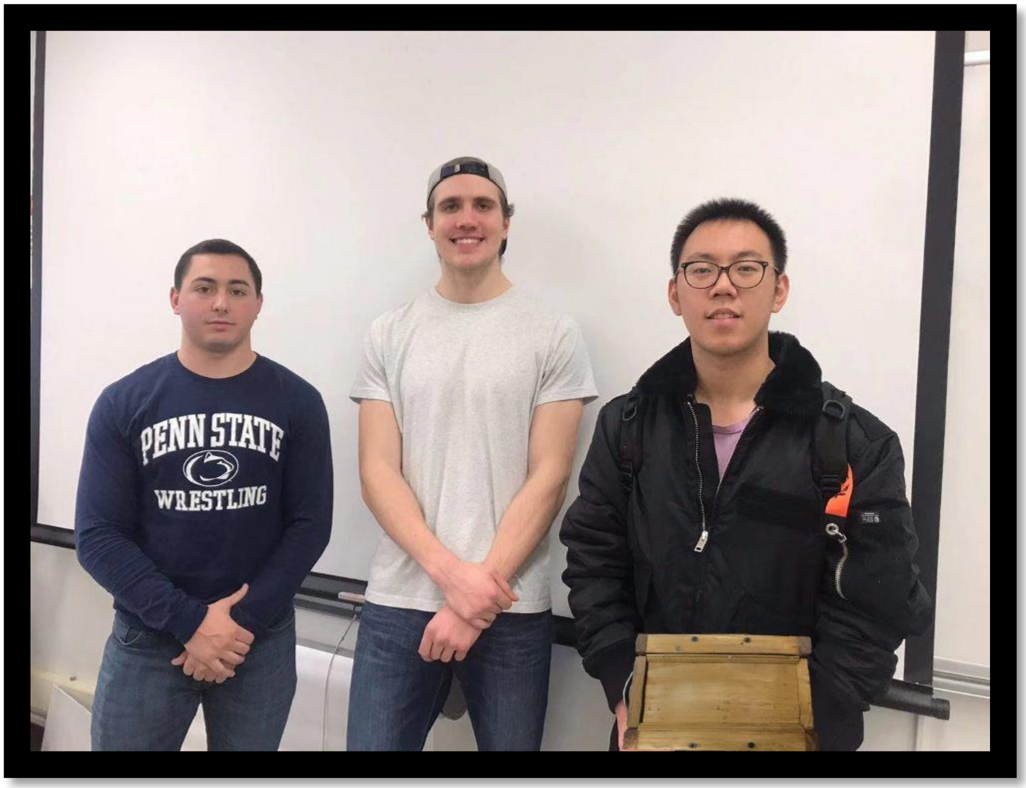

Figure A-1. Photo of design team with the STEM puzzle box. From left to right, the team members are Derek Verkleeren, Josh Kugel, and Yufan Wang. All three are mechanical engineering students at the Pennsylvania State University.

Josh Kugel is a senior biomedical and mechanical engineering student at the Pennsylvania State University with a focus in biomechanics. Originally from New Sewickley, PA, he spent this past summer in State College doing research for the Artificial Heart and Cardiovascular Fluid Dynamics Laboratory at Penn State. In lab, he has worked on projects working with bioprosthetic heart valve testing and mechanical thrombectomy projects dealing with the stresses of clot removal. Additionally, he worked on his capstone project for Lockheed Martin, fabricating a prototype to mode the real-time aerodynamic moments on rotary actuators at Mach speeds. Josh has gained valuable experience in CAD modeling and engineering applications through his project work and upper level class work. When he is not busy working on engineering projects, Josh enjoys lifting at the on-campus gyms and working on his motorcycle.

Derek Verkleeren is a junior in mechanical engineering at the Pennsylvania State University. Originally from Belle Vernon, PA just outside of Pittsburgh, he had an internship this past summer in Corpus Christi, Texas with Infrastructure and Energy Alternatives (IEA).

While in Texas, he worked on a large-scale wind turbine project with Siemens turbines. He had scholarship offers to wrestle at the University of Wisconsin and Iowa State University, but chose to focus on engineering at Pennsylvania State University's distinguished program. His hobbies include lifting at the IM Building and wrestling with the NLWC. His father and two uncles are all Pennsylvania State College of Engineering alumni. One fun fact is that his personal best time for solving a Rubik's Cube is 36 seconds.

Yufan Wang is junior in Mechanical engineering at Penn State University. His hometown is China. He has been studied abroad in U.S for 5 years. Three years in college, he gained lots of experience in CAD design with SolidWorks and CFD software. The drawing technique and aesthetic feeling developed from his Art minor contribute to his success in the Engineering projects. When he is not busy, he is always playing pool in the break zone in the HUB. He is a pool player for Penn State and a league member at Champs Downtown. During the team match against Carnegie Mellon University, he earned 4 points and helped his team win the match. One fun fact about Yufan is that he doesn’t spend his time sleep, but practicing pool in the Break zone. You can always see him near the pool table!

Appendix B: How to Open the Puzzle Box

The critical parts of the box include the components necessary to the opening mechanisms. Following the instructions below will lead to successful opening of the box:

1. *Open the magnetically closed lid.* The correct lid to open can be found with a few tricks. The first trick is to look at the symmetry of the box and deduce which piece of trim is fixed differently than the other three. The second trick is to use a compass to find the side with the magnet. When the magnetic lid is found, pull it off from the frame of the body.

Figure B-1. Box in its closed state. The user is to take off the lid currently located on top of the box in this image.

2. *Roll the balls into the hole in the center of the maze.* One of the first things a user will notice when taking off the lid is a 3D printed maze with a couple metal bearing balls rolling around. The trick is to get all these balls into the center of the maze so that a circuit below the maze can be complete.

Figure B-2. Image of the maze located inside the box. The maze is covered in acrylic in the final design. The goal is to get the metal ball bearings into the hole in the stomach of the person on the maze.

3. *Solve a coded mechanism in order to unlock a code.* In order to give a hint on the box, the user will need to solve a 3D printed combination lock on the outside. This will allow the user to get a four-digit code into the keypad.

4. *Enter the code into the keypad.* Once the maze is solved, the LCD screen will light up and prompt for a password to be entered. One the mechanism in the prior step is solved, the code can be entered into the keypad. The LCD will respond with options of the password being either correct or incorrect and will open a solenoid for a correct answer.

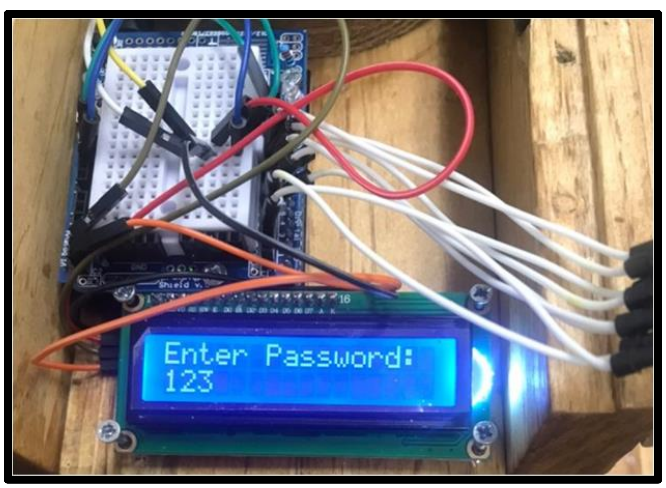

Figure B-3. LCD prompting for a password input.

5. *Open the door.* One of the outside walls will have a handle attached and whenever a correct password is entered, it will be able to open. This will be distinguished by a clicking sound coming from inside the box. Currently, the password is set at 123A.

Figure B-4. LCD confirming that the solenoid is in its open state. Front door will be able to be opened at this time.

Appendix C: Arduino Code and Pin Layout

The code below is currently programmed into the microcontroller. The correct password is 123A and can be adjusted by uploading new code. The wire to attach the microcontroller to the computer is placed inside the box. The pin layout is currently as follows: Keypad is in pins 2-9. The LCD is controlled by pins A4, A5, 5V, Ground. The Relay is controlled by pin 12, 5V, Ground.

```
#include <Keypad.h>
#include <Wire.h>
#include <LCD.h>
#include <LiquidCrystal_I2C.h>
#define I2C_ADDR 0x27
#define BACKLIGHT_PIN 3
#define En_pin 2
#define Rw_pin 1
#define Rs_pin 0
#define D4_pin 4
#define D5_pin 5
#define D6_pin 6
#define D7_pin 7
#define Password_Length 5

LiquidCrystal_I2C lcd(I2C_ADDR,En_pin,Rw_pin,Rs_pin,D4_pin,D5_pin,D6_pin,D7_pin);

int signalPin = 12;

char Data[Password_Length];
char Master[Password_Length] = "123A";
byte data_count = 0, master_count = 0;
bool Pass_is_good;
char customKey;

const byte ROWS = 4;
const byte COLS = 4;

char hexaKeys[ROWS][COLS] = {
  {'1', '2', '3', 'A'},
  {'4', '5', '6', 'B'},
  {'7', '8', '9', 'C'},
  {'*', '0', '#', 'D'}
};

byte rowPins[ROWS] = {9, 8, 7, 6};
byte colPins[COLS] = {5, 4, 3, 2};

Keypad customKeypad = Keypad(makeKeymap(hexaKeys), rowPins, colPins, ROWS, COLS);

void setup(){
  lcd.begin(16,2);
  lcd.backlight();
  pinMode(signalPin, OUTPUT);
}
```

```
void loop(){

  lcd.setCursor(0,0);
  lcd.print("Enter Password:");
  digitalWrite(signalPin, HIGH);

  customKey = customKeypad.getKey();
  if (customKey){
    Data[data_count] = customKey;
    lcd.setCursor(data_count,1);
    lcd.print(Data[data_count]);
    data_count++;
    }

  if(data_count == Password_Length-1){
    lcd.clear();

    if(!strcmp(Data, Master)){
      lcd.print("Correct");
      delay(2500);
      lcd.clear();
      lcd.setCursor(0, 0);
      lcd.print("Welcome Back");
      lcd.setCursor(4, 1);
      lcd.print("Box Unlocked");
      digitalWrite(signalPin, LOW);
      delay(10000);
      }
    else{
      lcd.print("Incorrect");
      delay(3000);
      }

    lcd.clear();
    clearData();
  }
}

void clearData(){
  while(data_count !=0){
    Data[data_count--] = 0;
  }
  return;
}
```

References

[1] Isreal, Shoshana I. "BUILDING AMERICA’S FUTURE: STEM EDUCATION INTERVENTION IS A WIN-WIN." *whartonupenn*, edited by Arnav Jagasia and Tyler Knox, 1 Nov. 2017, publicpolicy.wharton.upenn.edu/live/news/2188-building-americas-future-stem-education. Accessed 9 Dec. 2018.