Senior Design: Phase I

Mechanical Automata - Group B6

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We pledge our honor that we have abided by the Stevens Honor System.

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Project Statement

The Morris Museum currently has an exhibit called "The Murtogh D. Guinness Collection," this exhibit is a collection of mechanical musical instruments and automata. The displays in the museum are pieces of art, beautiful to look at while still, but even more impressive as the mechanisms move. The museum shows historical concepts of engineering, and is working to display how these historic ideas have helped to create the world we now know. However, these machines are extremely intricate and fragile, and have to be kept far from the reaches of most people, especially children. Therefore, it has been proposed that as a senior design project, a more educational exhibit will be designed to help the kids learn about the mechanisms that surround them. Specifically, the goal of this project is to build a link between the historic concepts created through these automatons and mechanisms and the current concept of digital coding.

Coding, at its most basic level, means that an input of one thing, gives a specific output, and this thought process existed long before the invention of computers. The theory of coding can be found dated back to 87 BC, where the first "coded" artifact is estimated to be built, known as the Antikythera Mechanism. This artifact used the input as the current date, and the output was then the exact positioning of the moon and sun. This artifact used an estimated 37 different gear sets to transfer the data initially put in to the desired output. Binary coding is much simpler than this, as it is made up of either something is there, or something is not, and depending on the pattern that it makes, a certain outcome is created. The thought process of this stems from the Jacquard machine, which is a programmable loom using holes punched in a set of cards. The holes in the cards represent the same thing as zeros and ones in current binary code. Further detailing of the Jacquard machine can be found in the *Literature Review* section of this report.

The goal of this project is to design an exhibit to be used as a learning tool for kids, preferably ages K-12. The model therefore has to be educational and interesting enough for kids. The model should also be large enough for multiple kids to view the model at once. Most importantly, the model should also be simple enough that kids can understand the workings of it, but still complicated enough that it piques their interests. It is also important to consider the types of machines the museum already has in its exhibit, as the proposed idea should be something unique and not just a remade version of a model already displayed. In order to properly design this exhibit, further research had to be done on the history of coding and the theory behind coding. This research can again be found in the *Literature Review* section.

The most effective way to test this project will be to see how kids interact with the design that the team produces. This would not only show if the kids are able to understand the display, but it would also show if they are interested in it. It will also be challenging to prototype this exhibit, as currently the team is working from a virtual standpoint due to the COVID-19 pandemic. Further ideas for testing and prototyping the project will be discussed later in this report.

Literature review

The following is a review of three devices in order to provide a guideline for the team's own design. Since the proposed educational exhibit is not comparable to anything currently on the market, the team chose to review several antique examples of programmable automata in order to gain sufficient background knowledge in the area of preliminary "computer science" and binary code.

The Writer

To begin the literature review, the group wanted to explore some of the oldest forms of automata in existence to gain a better insight into the history of this mechanical art form. One of the most famous examples of antique automata is known as "The Writer". This is a piece crafted by Pierre Jackquet Droz in the late 1770's. Despite the fact that it is over 240 years old, it is still a mechanical marvel. "The Writer" is pictured below in Figure 1. From the front this appears to be a simple doll at a writing desk. The back view reveals the intricate system of mechanisms that allows "The Writer" to blink his eyes, move his head, and write customizable messages up to 40 characters long on the paper in front of him. The whole device contains over 6,000 custom-made miniaturized parts and requires no external power source.

Figure 1: "The Writer"

One of the things that makes this device so incredible is the "programmability" of it. It is this element that sometimes earns this automaton the title of "The First Computer". The boy can write up to 40 characters in any combination across four lines. The programmability of it all is controlled by a wheel who's letters and characters can be arranged in any combination. At the core of the boy is a large stack of cams (pictured below in Figure 2) that can move vertically so that three cam followers can come into contact with different cams depending on which letter the automaton intends to write. The unique profile of each cam controls the shape of each character as well as the pressure with which the character is written. This creates an elegant script. This device was helpful to research because it combines a complex mechanical system with a bit of ancient “computer science”. The team hopes to accomplish the same seamless integration of mechanics with binary coding.

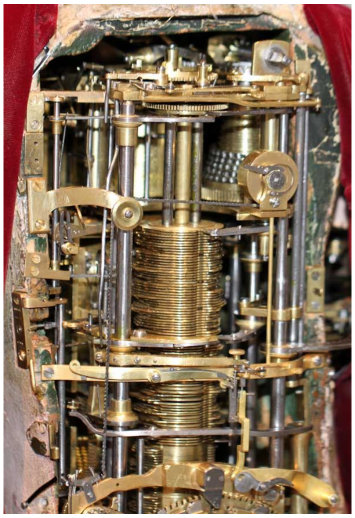

Figure 2: Stack of Cams Within “The Writer”

Music Boxes and The Polyphon

Another idea that perfectly combines antique mechanics and simple binary “code” is the music box. In the 18th and 19th centuries, music boxes were actually used less for decoration and more for serious entertainment and parlor music. In some cases they were as big as cabinets or dressers. At the basis of most any music box exists a metal comb that has prongs of varying lengths. Upon plucking a prong it will vibrate at a specific frequency which is what causes the sound. The longer the prong, the lower the note, and vice versa. Furthermore, the longer prongs are often weighted more at the ends which produces an even lower resonance. The added weight at the ends allows the comb to be more compact and still produce the same notes as a longer, unweighted comb. There are several different types of music box mechanics, but most commonly a cylinder with various protrusions is used to pluck the comb prongs in a specific order. Pictured on the next page in Figure 3 is a basic comb and cylinder setup. The cylinder’s protrusions perfectly illustrate the basic concept of binary code which is that there are two possible inputs (protrusion or no protrusion). A series of these inputs is what creates songs from the music box.

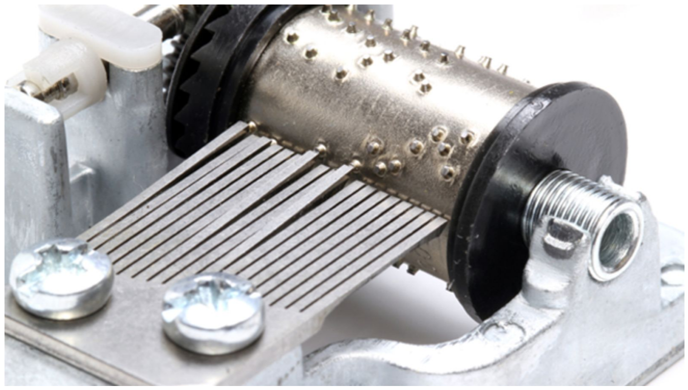

Figure 3: Music Box Comb and Barrel

As opposed to the cylinder, the music box's "code" can also come in the form of a paper with punched holes or even a disk. The ones that operate with a disk are referred to as polyphons (picture below in Figure 4). Polyphons look much like record players and even have interchangeable disks that can play different songs. Similar to the coded cylinder, these disks have bumps on them that strike the comb in exactly the right sequence. Just as "The Writer" was, the polyphon is another example of mechanics combined with coding. Some of the mechanical elements in music boxes include gears, cranks, and clock springs.

Figure 4: Polyphon

Devices of this type are of particular interest to the group since they are closest to the proposed design. Since part of the group's proposed exhibit deals with recreating a traditional hole punch operated music box, research in this area was of the utmost importance. Studying older designs like these can give the group the background knowledge needed in order to regenerate this design in a kid-friendly fashion. The difference between the antique machines and the suggested design is the fact that the team's design will also be Arduino powered in order to demonstrate the shift between ancient and modern coding in such devices. The planned exhibit is also geared towards children and for that reason will be much sturdier and easier to understand than traditional music boxes or polyphons.

Jacquard Devices

The Jacquard mechanism is another marvel of ancient computer science. Patented in 1804, a Jacquard mechanism affixes to a loom and allows intricate patterns to be woven by even the most unskilled of workers. Similar to some music boxes discussed in the earlier section, a Jacquard mechanism utilizes hole punched cards to act as the “code” for the pattern. To prepare the punch cards the rug or textile design is painted onto a paper which is overlaid by a grid. For the squares that are blank, a hole is punched in the card. The painted squares are left unpunched. These cards are pictured below in Figure 5. The various cards that make up one design are strung together and then fed through the Jacquard mechanism which rests atop the loom. The card is pushed towards a series of pins; if the pin passes through one of the holes, a hook is activated which weaves thread. If there is no hole for the pin to pass through, the hooks will not be activated. The punch card acts as a form of binary code since there are only two inputs: punched or unpunched. The combination of punches and blank spaces is what creates the textile patterns.

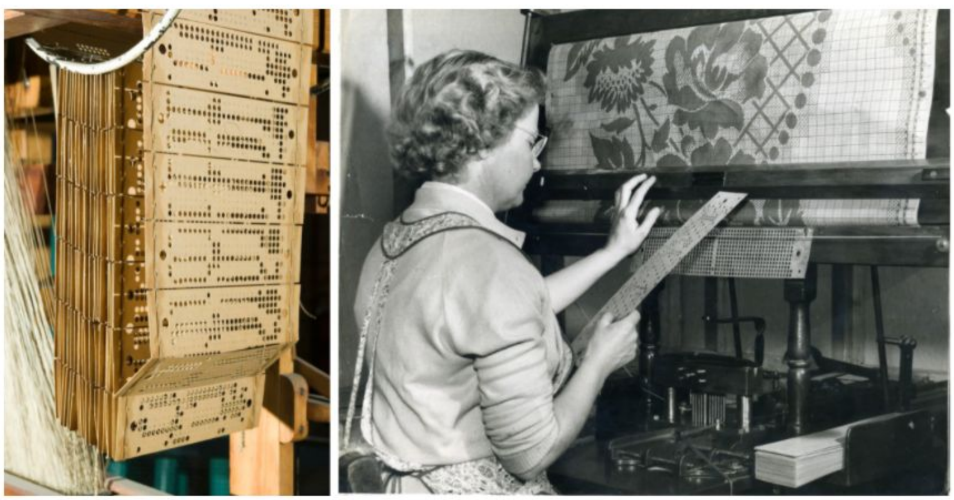

Figure 5: Punch Hole Cards for Jacquard Mechanisms

Needs and Specifications

Societal

Because the team's design is intended to be on display at the Morris Museum, it aims to serve the citizens of New Jersey and the greater Tri-State Area by serving as an educational tool for the youth. Despite the fact that the intended age range of the target audience will primarily be children (K-12), the exhibit will be educational to all, in demonstrating a historical link between traditional mechanical automata and present day concepts of coding/programming. Due to the rapid technological developments of the 19th and 20th Centuries, it can be difficult for some to envision how we got from point A to B. This exhibit will create a transitional link, where one may not clearly exist, within the familiar context of a particular feat of Mechanical Musical Automata. The team's design will ultimately serve all Museum visitors by delivering a safe, captivating, and insightful educational experience.

Stakeholders

In order to make the most of our design and properly address all areas that the finished product should, the team has procured a list of project Stakeholders. A stakeholder can be defined as any independent party that has a particular interest or concern in the matter at hand. Primary stakeholders are those who directly influence the direction of the project, while secondary stakeholders are those who will indirectly play a role in the process or indirectly influence the project.

Primary Stakeholders

- Senior Design Project Team
- Project Advisor, Professor Fontaine
- The Morris Museum
- Senior Design Project Review Board
- Mechanical Engineering Department

Secondary Stakeholders

- Museum Visitors
- Children (age K-12)
- Parents/Guardians of Museum Visitors
- Museum Representatives/Staff

Customers

In this particular instance, the team will not be marketing the design towards customers, as we do not intend to create or enter a particular market. Instead, the Morris Museum is our sole intended customer, but the project's success will depend heavily on the opinions and feedback of our target demographic (Museum visitors in the age range of K-12). Therefore, the team has conducted several customer interviews in the interest of capturing the voice of the Museum, as well as the interests of those who will directly benefit from the design. After the team conducted 3 separate customer interviews, the voice of the customer was analyzed in order to procure a list of interpreted customer needs. These interpreted needs were then ranked by the team in order of importance. The list can be viewed below in Table 1.

Table 1: Interpreted Customer Needs

No.	Customer Need	Importance (1-5)
1	*The exhibit can be operated by the museum educator*	5
2	*The exhibit demonstrates a relationship between 19th & early 20th century programmable technology and basic modern programmable technology*	5
3	*The exhibit is educational and age appropriate for the K-12 age bracket*	4
4	*The exhibit is challenging to the target demographic*	3
5	*The exhibit can be experienced both visually and aurally*	5
6	*The exhibit is relevant and engaging to young audiences today*	4
7	*The exhibit demonstrates the concept of binary coding*	4
8	*The exhibit is designed to incorporate a digital interface*	3
9	*The exhibit incorporates a hands-on activity for museum visitors*	3
10	*The exhibit can be fully demonstrated within 10-15 minutes*	4
11	*The exhibit plays contemporary popular music*	4
12	*The exhibit is interactive in nature*	4

After ranking the interpreted customer needs, the team created a list of metrics in order to convert the need statements into measurable goals. Because we were not interviewing on the basis of a single product/task and many of the need statements are subjective and descriptive in nature, many of the metrics that will be integral to the physical design of our exhibit are not yet known. These metrics will be identified beyond Phase 1. The list of metrics derived from the interpreted customer needs can be found below in Table 2.

Table 2: List of Need Metrics

Metric #	Need #	Metric	Units
1	1,8,12	Exhibit's Mechanical/Sonic Flexibility	# of unique user inputs/outputs
2	1,2,4,6	Stakeholder Opinion	Survey
3	3,4	Scholastic Subject Matter	Common Core Standards, School Curriculum
4	5,11	Exhibit Volume	dB
5	6,11	Song Popularity	Music Charts Rating, Itunes/Spotify Top 40
6	7	Relevance to Binary Coding	# of input/output states
7	10	Exhibit Demonstration Duration	Minutes
8	11	Song Age	Years

In order to break down the customer requirements into segments and identify the means for achieving each segment, the team organized the identified needs and metrics into a Quality Function Deployment (QFD). The QFD will not only serve to provide the team with a logical view of the selected critical aspects of the project, but also allow for the formulation of technical priorities, benchmarks, and targets, that will carry through to later Design Phases. The QFD can be viewed in Section A of the Appendix and Figure 12.

Concept Generation

Concept 1: The Music Box

The first concept that the team generated was to use the context of a mechanical music box to demonstrate a link between 19th and 20th Century pinned-cylinder music boxes and how the same task may be accomplished through coding/programming songs today. While pinned cylinders were effective, they took a lot of time and effort to craft and were usually not interchangeable, making them only capable of playing a single song. While programmable music boxes have also been around for some time, one would have to punch out notes on a roll of paper and feed the card through the music box while turning a hand crank to play. These music boxes demonstrate the idea of binary code in a similar fashion to the programmable loom/Jacquard Machine. If a hole is punched out, the respective note sounds. The team's idea would involve constructing a similar music box and using programmable electrical components such as DC motors, Servo motors, or solenoids to drive gears/hammers, which will ultimately pluck the comb to sound a note. Using these components in conjunction with Arduino code will allow us to control the music box's inputs/outputs in a more modern fashion, with the flexibility to play any song, either by pre-coding or via a digital/keyboard interface that works in real-time (press a key and a note sounds). By specifying which motors are driven in each time interval and for how long, the user can code a host of songs and melodies, in a comprehensive interface, to play autonomously. Demonstrating the function of such a music box in contrast to a more traditional, pinned-cylinder music box would be an effective way of creating a link between traditional, purely mechanical music boxes and modern, low-level coding/programming techniques. The team envisions educating museum guests, through demonstration, on how traditional programmable music boxes function and then turning to our music box to play the same song, as well as some modern songs to capture the audience's attention, demonstrating the flexibility, ease, and endless possibilities that low-level programming unlocks. Because the driven electro-mechanical elements (motors/solenoids) have two states (On/Off), the team's music box idea would accomplish the same task, using the same fundamental idea, in a more contemporary fashion. A detailed conceptual sketch can be viewed on the next page in Figure 6.

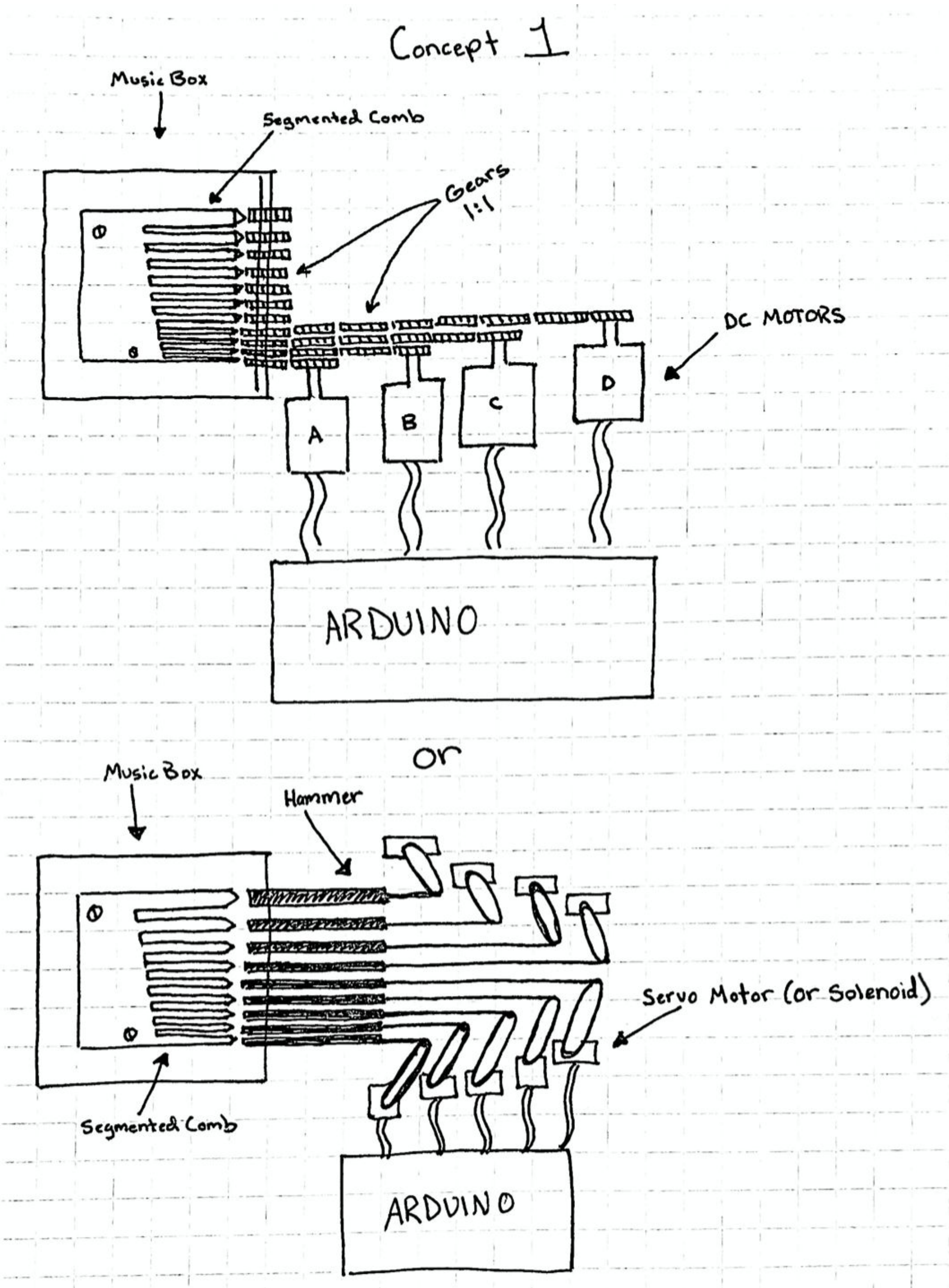

Figure 6: Concept 1 Sketches

Concept 2: The Typewriter

The second concept that the team decided to explore was a typewriter machine due to its 19th century origins. Since a typewriter is the first mechanical system that mirrors what a computer keyboard looks like today the team decided that this would be an efficient and relatable way to demonstrate the link between mechanical and digital versions of binary coding. The original typewriters that have existed in the past are fully mechanical and utilize a simple mechanism that involves levers and hammers. Each of the 26 letters of the alphabet and additional symbols is attached to a small hammer. Manually pressing a key triggers a hammer with the corresponding letter or symbol stamp that swings up towards the paper. As this happens an ink cloth is also lifted up and sandwiched between the hammer and the paper to create the appropriate impression. The keys are attached to springs that force these hammers up and down as the keys are pressed and released. The team figured that this concept of pressing and releasing keys to trigger a spring accurately represents the concept of using a 1 or a 0 to produce a variety of different outputs. Modern digital computer keyboards utilize a similar concept but instead of triggering a mechanical mechanism pressing each key triggers a specific binary code pattern that the computer then translates to a specific letter.

The proposed design for the exhibition involves creating a simple typewriter machine with all 26 letters of the alphabet that utilizes the spring, hammer, and stamp mechanism to allow for typing. This exhibit has the potential to be highly interactive as the museum visitors would be able to manually type and witness how this mechanism works. This could be accomplished by creating a larger machine with the hammer mechanism visually open to show the movements as they occur. The device could also be made out of a clear material to show the internal components. In order to compare the typewriter to modern digital coding, the team would then create a digital interface that is attached to a keyboard. As the visitors type on the keyboard the interface could display the binary patterns that correspond to each letter of the message, as well as the worded translation shown below, in real-time. This exhibit would also include a worded explanation that describes the typewriter mechanism more in depth as well as the way in which a computer reads and processes binary code. A conceptual sketch can be seen on the next page, in Figures 7 and 8, showing the team's idea more clearly.

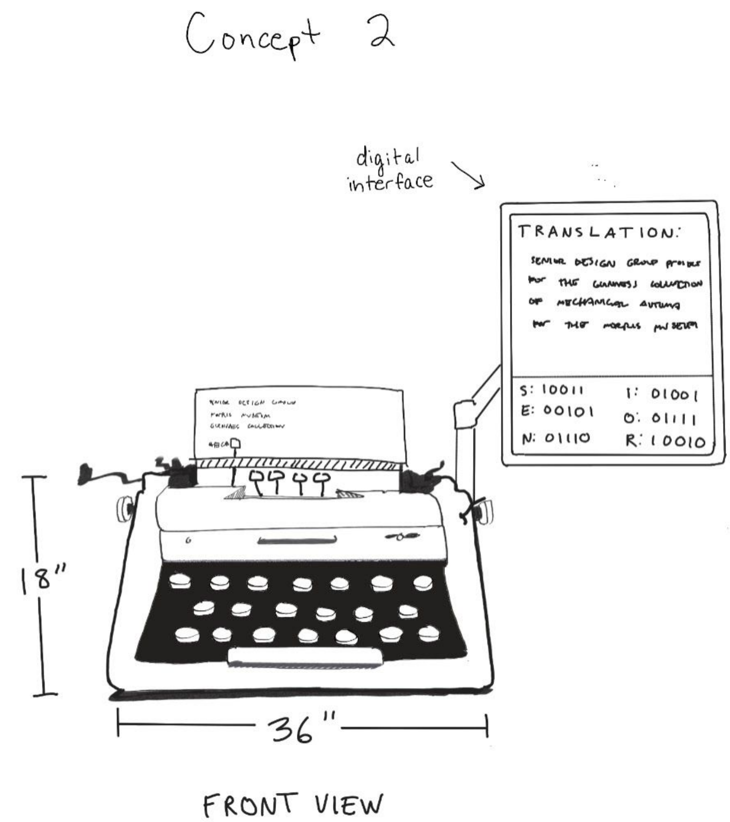

Figure 7: Concept 2 - Front View Sketch

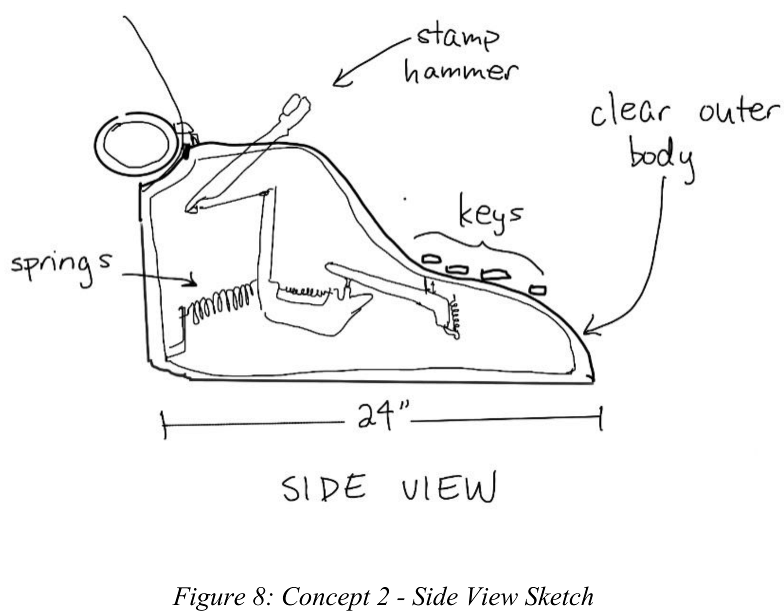

Figure 8: Concept 2 - Side View Sketch

Concept 3: The Piano

The third and final concept that the team devised is that of a simplified piano. A piano perfectly demonstrates the use of binary code through music since there are two inputs: pressing a key or not pressing a key). Pressing a key will trigger a hammer to hit a specific string, generating a note. Of course, the other input, pressing nothing, will not generate a note. The proposed concept is a small piano (41 keys as opposed to the traditional 88). The piano will function as any normal piano would. This brings interactivity into the exhibit and allows children to play a note with their hands. To demonstrate the difference between 19th century "code" and modern day code, the piano will also have solenoid motors on each hammer. The motors can be switched into two positions: on or off. Again, the on position will trigger the hammer to play a note. The off position will generate no response. Through these mechanisms, a song can be played and viewers of the exhibit will be able to see how the idea of binary code is still used, but in a more modern sense. The piano will be open at the top which allows for the inner mechanisms to be appreciated. Traditional upright pianos are approximately five feet tall and five wide. The proposed design should be around four feet tall and four feet wide. This size is suitable for the kids and preteens at which this exhibit is aimed. A step stool next to the piano allows for smaller children to see into the top of the piano and get a better understanding of the mechanisms. A detailed concept sketch can be seen on the next page in Figure 9. Similar to the concept of the music box, this design will capture the audience's attention by its ability to play a multitude of tunes, both classical and more modern.

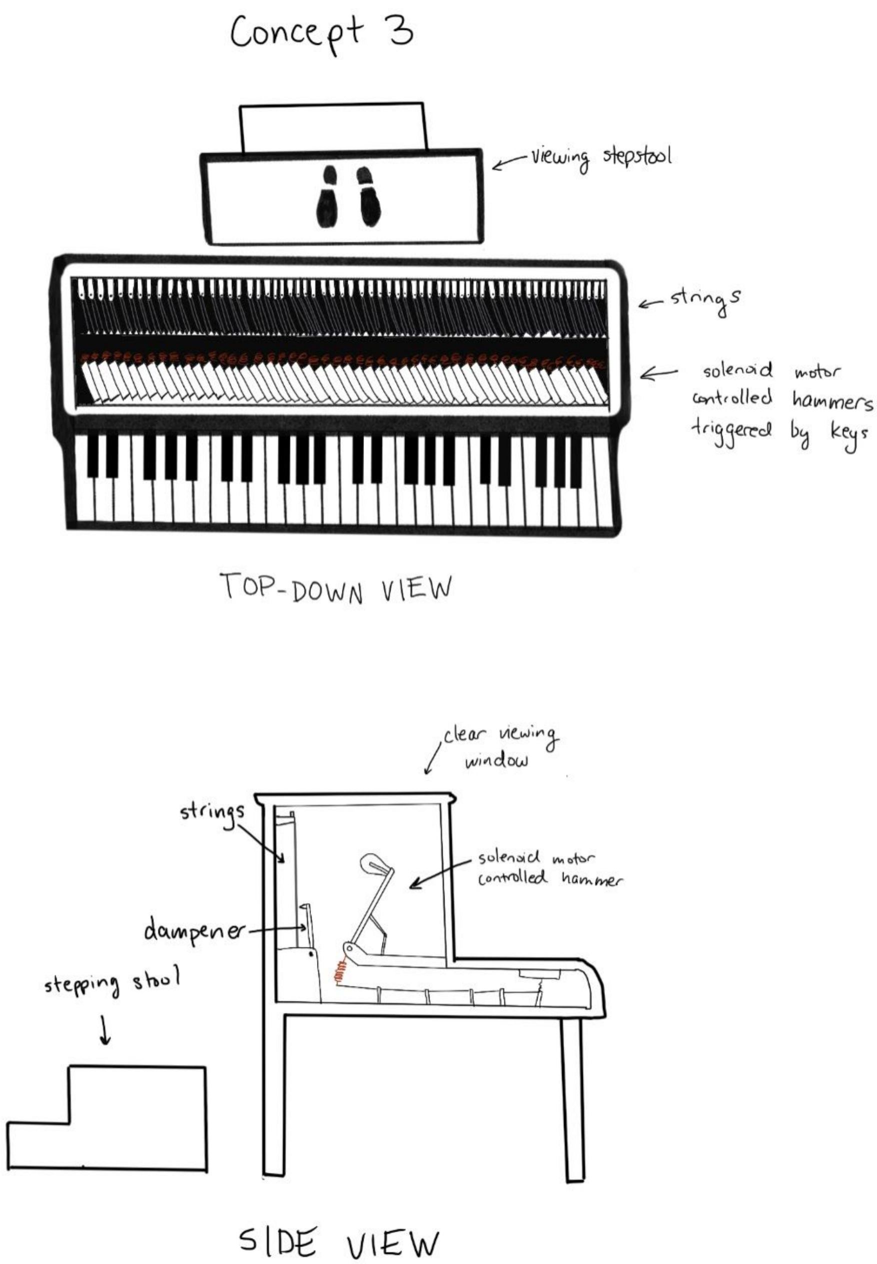

Figure 9: Concept 3

Concept Selection

The team put together a Concept Combination Matrix, shown below in Table 3, to determine which of the aforementioned concepts stood out, based on a list of the relevant selection criteria. This helped bring about a better understanding of how each concept fared against its counterparts in specific categories. Upon review of the screening matrix, it appeared that the Music Box showed the most promise, ranking first among its competitors.

Table 3: Concept Combination Matrix

	Music Box	Typewriter	Piano
Selection Criteria	Rating	Rating	Rating
Operable by museum staff	+	+	+
Minimal handling necessary	+	-	-
Interactivity/User Engagement	+	+	+
Educational Value	+	0	0
Entertainment Value	+	0	+
Ease of Use	+	-	0
Technological Revelance	+	0	0
Cost	0	+	-
Sames	0	3	3
Minuses	0	2	1
Net	0	-2	-1
Rank	1	3	2
Continue?	Yes	No	No

Another round of comparison was performed through the use of a Concept Selection Matrix, shown on the next page in Table 4. This allowed the group to assess the advantages and disadvantages that each concept had over the others when the weight of importance for each of the selection criteria was factored into the equation. Weight was carefully distributed among the selection criteria and the concepts were scored accordingly. These matrices made it quite clear that the best contender to consider for the future product development stages of this project was the Music Box.

Table 4: Concept Selection Matrix

		Concepts					
		Music Box		Typewriter		Piano	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Operable by museum staff	0.1	3	0.3	3	0.3	3	0.3
Minimal handling necessary	0.05	3	0.15	1	0.05	1	0.05
Interactivity/User Engagement	0.2	3	0.6	3	0.6	3	0.6
Educational Value	0.2	3	0.6	2	0.4	2	0.4
Entertainment Value	0.05	3	0.15	2	0.1	3	0.15
Ease of Use	0.1	3	0.3	1	0.1	2	0.2
Technological Revelance	0.2	3	0.6	2	0.4	2	0.4
Cost	0.1	2	0.2	3	0.3	1	0.1
	Total Score	2.90		2.25		2.20	
	Rank	1		2		3	
	Continue?	Yes		No		No	

Technical Analysis

Areas for Phase 2

Musical Frequencies

Since the team is moving forward with Concept 1, the music box, it is vital that the device is able to produce an appropriate melody to stress the importance of the type of outcome that results from binary programming. Sound is created by vibrating particles that produce waves that can travel through a medium like water or air, though air will be the only focus in the case of this project scope.

Sound exists in the form of longitudinal, or compression, waves, which are shown in Figure 10 below. These types of waves are defined by the fact that the particles vibrate in the same direction as the movement of energy in the form of the wave. Longitudinal waves have several important characteristics that must be fully understood to properly construct a music box that creates an appropriate melody. As these waves move through the air, vibrating particles are pushed closely together and then pulled apart in periods referred to as compression and rarefaction, respectively. In the case of longitudinal waves, the wavelength (λ) is defined as the distance between two consecutive points that are in the same phase. This can be seen in the

Figure 10 below as the wavelength extends between the center of the two compression regions. The amplitude is the maximum particle displacement from a position of rest.

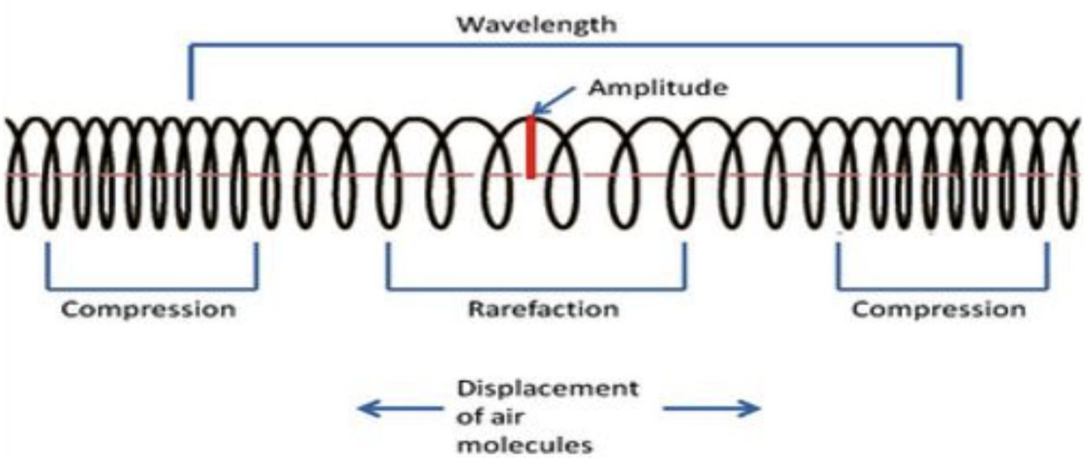

Figure 10: Longitudinal Wave

These physical characteristics of longitudinal waves combined with the rate and speed at which they occur are responsible for creating the characteristics of the sound we hear as it hits our ears. The frequency (*f*) of a wave is the number of wavelengths that pass through a fixed point per second. The SI unit to measure frequency is Hz, which is defined as one wavelength per second. The period (T) of a wave is the reciprocal of frequency as it is defined as the time it takes for one full wavelength to pass a fixed point:

$$T = \frac{1}{f}$$

Knowing this, the speed (v) of a wave is directly proportional with both wavelength and frequency, and can be defined by the equation shown below. It is known that the speed of sound as it travels through air at room temperature is approximately 343 m/s.

$$v = \lambda f$$

Frequency is often referred to as pitch, or notes, when speaking about music. These pitches determine how high or low a note sounds, therefore a combination of different pitches is what creates the distinct melody of a song. The chart in Figure 11 below shows the common musical notes used to write music aligned with their corresponding frequency ranges.

Note	Frequency (Hz)		
	Minimum	Ideal	Maximum
C3	260.12	261.63	263.14
C#3	275.59	277.18	278.79
D3	291.97	293.66	295.37
D#3	309.34	311.13	312.93
E3	327.73	329.63	331.54
F3	347.22	349.23	351.25
F#3	367.86	369.99	372.14
G3	389.74	392.00	394.27
G#3	412.91	415.30	417.71
A4	437.47	440.00	442.55
A#4	463.48	466.16	468.86
B4	491.04	493.88	496.74
C4	520.24	523.25	526.28
C#4	551.17	554.37	557.58
D4	583.95	587.33	590.73
D#4	618.67	622.25	625.86
E4	655.46	659.26	663.07
F4	694.43	698.46	702.50
F#4	735.73	739.99	744.28
G4	779.48	783.99	788.53
G#4	825.83	830.61	835.42
A5	874.93	880.00	885.10
A#5	926.96	932.33	937.73
B5	982.08	987.77	993.49
C5	1040.47	1046.50	1052.56

Figure 11: Musical Notes and Frequencies

Based on these concepts the team must be able to ensure that the mechanical music box, both with and without the assistance of the Arduino and motors, is able to accurately produce all of these frequencies so that common songs can be produced. The intensity, or loudness, of sound is another factor that must be considered as the team must ensure that the notes produced are not too quiet for the audience to hear and not too loud to the point where their ear drums are injured. Sound intensity is related to the amplitude of the longitudinal waves and is given by Watts per square meter (W/m^2). Sound intensity is related to the threshold of hearing for the human ear through decibels (dB), which are calculated as follows:

$$L = 10log(\frac{I_2}{I_1})$$

L = *The number of decibels* I_2 *is greater than* I_1

I_1 = *Lower sound intensity being compared*

I_2 = *Higher sound intensity being compared*

Sound intensity must be made relative to the threshold of human hearing to accurately portray what the power level of a sound is. This value, which is designated by I_1 in the above equation, is 1×10^{-12} W/m^2. Based on decibel levels for standard sounds, the aim for this device would be to produce a sound somewhere between eighty and one hundred decibels, as these audio levels are similar to those of humans talking loudly and yelling, respectively.

As shown in the Concept 1 sketch in Figure 6, the music box will work by having either a hammer or gear strike a segmented comb. This interaction will produce vibrations that will create the sound frequencies described above. The geometric and material features of the comb and hammer or gear will affect the frequency and intensity of the sound produced. The segmented comb also has long rectangular prongs of different lengths. These different lengths will produce a variation of frequencies as the smaller prongs will produce relatively higher notes and the longer prongs will produce lower ones. The following equation can be used to decide on the appropriate physical features based on the desired frequencies:

$$f_n = \frac{n v_L}{2L}$$

$$v_L = \sqrt{\frac{E}{\varrho}}$$

$E = Young's\ modulus\ of\ elasticity\ of\ material$

$\rho = Density$

$L = Length\ of\ the\ rod$

$n = 1, 2, 3...$

This equation will help the team with the preliminary steps of selecting an appropriate material for the comb and barrel based on the desired frequency range and elastic modulus. This will also help with setting the relative lengths of each segmented end of the comb. It is also expected that some trial and error combined with this mathematical analysis will be required to ultimately produce the desired notes. A frequency meter could potentially be used to measure the frequencies being emitted from the hammer and comb, and the group can refine the dimensions of the device based on the values being received.

Electrical Components

The Concept 1 sketch in Figure 6 shows that the project plan will involve the use of several DC or solenoid motors, depending on the direction the team decides to go in. These motors will be attached to the hammer or gear portion of the music box and will be responsible for moving it to hit the prongs and produce vibrations. Depending on the types of songs that are programmed into the Arduino, these components will be required to move at different speeds. These motor speed requirements will be developed in Phase 2 as the team moves forward with the programming of the device, and based on this a motor model will be able to be selected with the appropriate voltage and current parameters to produce the desired RPM. The following equation will allow for the power consumption (P) of the device to be calculated as it operates:

$$P = IV$$

I and V are equal to the maximum current and voltage running through the motor, respectively. The power that the device consumes must be minimized as to not require too much of an electric cost for the museum to run. This value will also likely need to be reported to the museum as the device is constructed.

Research on Similar Systems

Figure 3 in the Literature Review section above shows a traditional music box with a comb and barrel. As discussed earlier, the small extrusions on the barrel hit the comb at the appropriate locations as it rotates to produce the desired frequencies. When researching the methods that are used to construct music boxes, it was found that the comb is constructed from carbon steel, which has a density of 7850 kg/m^3 and a Young's modulus of 200 GPa. The segmented ends of the comb are cut into a rectangular shape, and the material is hardened, quenched, and annealed to improve its durability and flexibility. It was also found that a solid block lead and tin block is attached to the end of the comb. This block provides extra weight to generate the lowest notes on the musical spectrum. As the team moves forward with development, the effect of additional force on frequency will also have to be analyzed. Carbon steel or materials of similar properties may be a good starting point for the material selection analysis as this has been successful when used in other similar instruments.

Other musical instruments are modelled using the concept of Pythagorean tuning. This is the concept that string lengths produce the best consonance between frequencies when they exist at 3:2 and 2:1 ratios. The smallest and largest frequencies should be at a 2:1 ratio in which the longest string is twice the length of the shortest one, and additional frequencies between those two values can then be added in by continuously dividing by 3/2. Following this system creates a series of different notes that are all in tune with each other and therefore sound of high quality to the human ear. This concept will likely need to be utilized when the team is creating the length of each segment of the music box comb as the device must produce notes of different frequencies that also sound consonant with each other. Based on this research it seems that a useful approach when constructing the comb geometry may be to establish the dimensions of the comb segment required to produce the smallest frequency value in the target range, and then deciding on the dimensions of the other segments based on these ratios used in other musical instruments.

Project Plan

By the end of this project, the main deliverables will be the models produced by the team. As the team has decided to move forward with the "Music Box" concept, there will be two separate models made. The first model will be a music box made using the pin and barrel concept, and the second model will be a music box made using digital coding. In the case that the team still has to work virtually, these models will be made in a virtual environment. There will also have to be a deliverable made that will propose the idea to the museum. This will demonstrate how the models fulfill their needs, and prove that it works. It is also possible that the team will have another deliverable for the museum to display alongside the models that will explain the concepts demonstrated. However, further detailing of the deliverables will be decided later on the project.

The Gantt chart was first made for this project in the beginning stages. It has been updated during each meeting with the progress made on each task, and when the task is estimated to be completed on. The Gantt chart also details who is responsible for completing each task, and who is responsible for reviewing each task. It is primarily broken down into the sections required for the reports, however, as other tasks were made, they were added to the Gantt chart. A detailed view of the Gantt chart used by the team can be found in the Section A of the appendix, Figures 13 and 14.

At this phase of the project, the budget is extremely hypothetical. It is currently broken down by the items the team believes will be needed for the project. The prices of the items are currently estimated in the budget as the team is still unsure of the materials and details of the proposed concept. Also, due to the COVID-19 pandemic, the budget is entirely theoretical as the team is currently planning to produce virtual models. To begin with, the team was given a budget of $700 from the Mechanical Engineering Department. This document will be further detailed as the project progresses. The current budget can be seen below in Table 5.

Table 5: Project Budget

Item	Cost	Remaining
Music Combs (x2)	$18	$682
Plywood	$14	$668
Paint/Varnish	$15	$653
Crank Handle	$5	$648
Hole Punch Music Sheet Paper	$5	$643

Discussion

In conclusion, the team has created a solid foundation for this project. While looking to create an educational exhibit for the Morris Museum, the team has completed several steps towards fulfilling their needs. A comprehensive analysis of several historical mechanisms have been researched in order to provide the team with a better knowledge of the technology they will be applying. By first researching “The Writer,” the team got a better understanding of how coding was historically defined, while by researching the “Jacquard Machine,” the team got an idea of where exactly binary coding was first applied. The research done on the music boxes and phonograms then led the team to developing the concept that was decided to move forward on. After collecting the customer needs, developing three different concepts, and comparing those concepts, the team concluded that the first concept proposed, the concept of the music box, most completely fulfilled the customer needs. For further analysis, the team also decided on areas that will be researched and tested further in the next phase of the project.

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Appendix

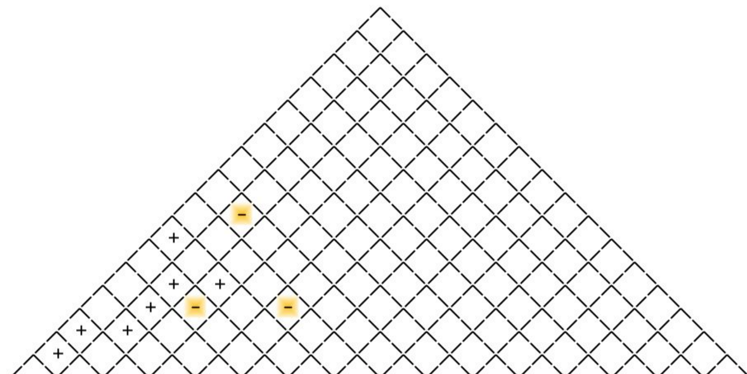
Section A

Figure 12: Quality Function Deployment

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
				Direction of Improvement	▲	▲	◇	▲	▲	▲	◇	▼								
Row #	Weight Chart	Relative Weight	Customer Importance	Customer Requirements / Technical Requirements	Mechanical/Sonic Flexibility	Stakeholder Opinion	Scholastic Subject Matter	Exhibit Volume	Song Popularity	Relevance to Binary Coding	Demonstration Duration	Song Age								
1		10%	5	Can be Operaterd by Museum Instructor	●	○														
2		10%	5	Relationship b/w Old and New Programmable Tech		●														
3		8%	4	Educational/Age Appropriate (K-12)			●													
4		6%	3	Challenging to Target Demographic		●	●													
5		10%	5	Can be Experienced Both Visually and Aurally				●												
6		8%	4	Relevent & Engaging to Young Audiences		●			●											
7		8%	4	Demonstrates Concept of Binary Coding						●										
8		6%	3	Designed to Incorporate Digital Interface	○															
9		6%	3	Incorporates a Hands-on Activity																
10		8%	4	Can be Fully Demonstrated in 10-15 min							●									
11		8%	4	Plays Contemporary Popular Music				●	●			●								
12		8%	4	Interactive in Nature	●															
				Technical Priorities	187.5	256.25	131.25	168.75	150	75	75	75	0	0	0	0	0	0	0	0
				Relative Weight	17%	23%	12%	15%	13%	7%	7%	7%	0%	0%	0%	0%	0%	0%	0%	0%
				Weight Chart																

Figures 13-14: Project Gantt Chart

Task Name	Duration	Start	Finish	Predecessors	Successors	Resource Names	Reviewer
Phase 1	**19 days**	**Mon 9/14/2(**	**Thu 10/8/20**				
Progress Update	**9 days**	**Mon 9/14/2(**	**Thu 9/24/20**				
Report	**8 days**	**Mon 9/14/2(**	**Wed 9/23/20**		**9**		
Meeting Minutes	4 days	Mon 9/14/2(	Thu 9/17/20			Jaymie	
Description of Project and Main Goals	8 days	Mon 9/14/2(	Wed 9/23/20		14SS,15SS,24,25,8,6	Jaymie	
List of Tasks Completed	0 days	Wed 9/23/2(	Wed 9/23/20	5		Lauren	
List of Tasks In-Progress	0 days	Wed 9/23/2(	Wed 9/23/20	5		Melissa	
List of Remaining Tasks	0 days	Wed 9/23/2(	Wed 9/23/20	5		Jesse	
Review	1 day	Thu 9/24/20	Thu 9/24/20	3			
Phase 1 Report	**17 days**	**Mon 9/14/2(**	**Tue 10/6/20**				
Report	**16 days**	**Mon 9/14/2(**	**Mon 10/5/20**		**53**		
Development	**15 days**	**Mon 9/14/2(**	**Fri 10/2/20**		**50,51,52**		
Project Statement	**7.5 days**	**Mon 9/14/2(**	**Wed 9/23/20**		**56**	**Jaymie**	
Motivation	6 days	Mon 9/14/2(	Mon 9/21/20	5SS			
Goals/Objective	6 days	Mon 9/14/2(	Mon 9/21/20	5SS	47,17,18		
Major Issues	**3.5 days**	**Fri 9/18/20**	**Wed 9/23/20**		**24,25**		
Design & Analysis	2 days	Fri 9/18/20	Wed 9/23/20	15			
Prototyping & Experimentation	2 days	Fri 9/18/20	Wed 9/23/20	15			
Literature Review	**9 days**	**Mon 9/14/2(**	**Thu 9/24/20**		**45,25,24,58**	**Lauren**	**Jaymie**
State-of-the-art Review	9 days	Mon 9/14/2(	Thu 9/24/20				
Commercial Applications	9 days	Mon 9/14/2(	Thu 9/24/20				
Needs & Specifications	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**		**57**	**Jesse**	**Lauren**
Customer Interview	12 days	Mon 9/14/2(	Tue 9/29/20				
Societal	5 days	Fri 9/25/20	Thu 10/1/20	5,16,19			
Customers	5 days	Fri 9/25/20	Thu 10/1/20	5,16,19			
Concept Generation/Selection	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**		**44,49,59**	**Bella**	**Jesse**
Concept Generation	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**		**41,42**		
Brainstorming	7 days	Mon 9/14/2(	Tue 9/22/20		32,36,40,30,34,38		
Concept 1 - Typewriter	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**			**Melissa**	
Strengths/Weaknesses	4 days	Mon 9/14/2(	Thu 9/17/20	28	31,35,39		
Write-up	6 days	Fri 9/18/20	Fri 9/25/20	30			
Annotated Sketch	7 days	Wed 9/23/2(	Thu 10/1/20	28			
Concept 2 - Music Box	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**			**Jesse**	
Strengths/Weaknesses	4 days	Mon 9/14/2(	Thu 9/17/20	28			
Write-up	6 days	Fri 9/18/20	Fri 9/25/20	30			
Annotated Sketch	7 days	Wed 9/23/2(	Thu 10/1/20	28			

◢ Concept 2 - Music Box	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**			**Jesse**	
Strengths/Weaknesses	4 days	Mon 9/14/2(	Thu 9/17/20	28			
Write-up	6 days	Fri 9/18/20	Fri 9/25/20	30			
Annotated Sketch	7 days	Wed 9/23/2(	Thu 10/1/20	28			
◢ Concept 3 - Piano	**14 days**	**Mon 9/14/2(**	**Thu 10/1/20**			**Bella**	
Strengths/Weaknesses	4 days	Mon 9/14/2(	Thu 9/17/20	28			
Write-up	6 days	Fri 9/18/20	Fri 9/25/20	30			
Annotated Sketch	7 days	Wed 9/23/2(	Thu 10/1/20	28			
Concept Screening Table	0 days	Thu 10/1/20	Thu 10/1/20	27			
Concept Selection Matrix	0 days	Thu 10/1/20	Thu 10/1/20	27			
◢ Technical Analysis	**6 days**	**Fri 9/25/20**	**Fri 10/2/20**		**60**	**Melissa**	**Bella**
Discuss Areas for Phase 2	1 day	Fri 10/2/20	Fri 10/2/20	26			
Cite Research on others models	1 day	Fri 9/25/20	Fri 9/25/20	19			
◢ Project Plan	**15 days**	**Mon 9/14/2(**	**Fri 10/2/20**			**Jaymie**	**Melissa**
Expected Deliverables	1 day	Tue 9/22/20	Tue 9/22/20	15			
Gantt Chart	1 day	Mon 9/14/2(	Mon 9/14/20			Jaymie	
Budget	1 day	Fri 10/2/20	Fri 10/2/20	26			
Discussion/Conclusions	1 day	Mon 10/5/2(	Mon 10/5/20	12			
References	0 days	Fri 10/2/20	Fri 10/2/20	12			
Appendix	0 days	Fri 10/2/20	Fri 10/2/20	12			
Review	1 day	Tue 10/6/20	Tue 10/6/20	11			
◢ Presentation	**11.5 days**	**Wed 9/23/2(**	**Thu 10/8/20**				
◢ Development	**10.5 days**	**Wed 9/23/2(**	**Wed 10/7/20**		**61**		
Project Statement	5 days	Wed 9/23/2(	Wed 9/30/20	13		Jaymie	
Customer Needs	2 days	Fri 10/2/20	Mon 10/5/20	22		Jesse	
State-of-the-art Review	3 days	Fri 9/25/20	Tue 9/29/20	19		Lauren	
Conceptual Designs	4 days	Fri 10/2/20	Wed 10/7/20	26		Bella	
Areas for Technical Analysis	3 days	Mon 10/5/2(	Wed 10/7/20	43		Melissa	
Review/Practice	1 day	Thu 10/8/20	Thu 10/8/20	55			