Design and Manufacture of the Quatraphone and Composition of a Short Piece

by

Jessica E. Chiafair

Submitted to the Department of Mechanical Engineering
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Abstract

This thesis describes the design and manufacture of a chromatic instrument, the quatraphone. This instrument is made of square metal keys that are struck by a wooden mallet activated by a lever action mechanism. Vibration and damping of the rectangular plates were analyzed for various materials in order to determine which material produced the most musical tones. Brass and aluminum were selected for the quatraphone design.

The final assembly was created with the objective of minimizing the instrument's size and its unique parts, while enabling simple disassembly to allow for easy repair of the instrument. The prototype includes fourteen tones, yet further developments could include additional notes in the chromatic scale and in several octaves. An original composition, entitled *Prelude*, was composed for the quatraphone in order to present the distinct sound qualities of this new instrument.

Thesis Supervisor: Barbara J. Hughey, PhD
Title: Technical Instructor, Department of Mechanical Engineering

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Contents

List of Figures

List of Tables

1 Introduction

Music is played throughout the world on a variety of musical instruments. There are instruments that are unique to the particular culture in which they are played, and there are instruments that are generally the same in every culture, such as those found in an orchestra or wind ensemble. Throughout the world new instruments are developed, by large companies or by independent musicians in their homes. The new designs are made either to produce a new sound or improve on existing instruments.

Creating a new instrument involves the use of mechanical engineering as well as musical skills. The design and construction of the instrument itself are primarily mechanically oriented, making the instrument conducive to playing comfortably, accurately and in an appealing manner. The composition and playing of a piece of music requires the work of a musician.

The design for this new instrument incorporates various elements from existing instruments. The idea originates from a carillon but uses aspects of the piano, xylophone and glockenspiel. This thesis describes the development of the quatraphone, a musical instrument comprising square metal keys that are played by a lever action mechanism. Additionally, a musical piece entitled *Prelude* was composed for this new instrument.

2 Background

Various instruments were combined in the design of the quatraphone. The combined instruments include the carillon, piano, xylophone and glockenspiel. A description of each of them is included in Section 2.2. All of these instruments use the chromatic scale, the basis of most Western music. A short discussion of frequency to pitch relationships and tuning systems is presented below.

2.1 Frequency to Pitch Relationships and Tuning Systems

In an equal temperament scale, the interval between each half step, the semitone, is the same. The twelve half steps in each octave, shown between C1 and C2, are labeled below on the keyboard in Figure 1 [1].

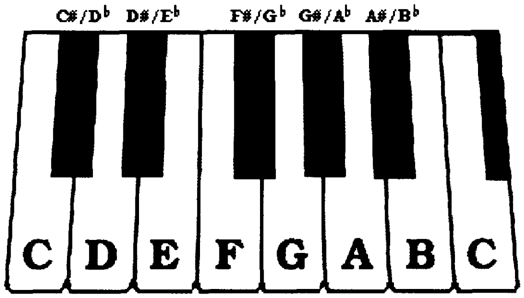


Figure 1: Pitches on keyboard.

The frequencies of an octave have a ratio of 2:1. For example,

$$f_{C2} = 2f_{C1} \tag{1}$$

Similarly, a perfect fifth interval has a ratio of 3:2. On the keyboard above, a perfect fifth is the distance between C1 and G. Table 1 lists the frequency ratios of common intervals with the pitch names listed to define the interval.

Table 1: Frequency ratios for common intervals.

Ratio	Half Steps	Interval	Keyboard Pitches
2:01	12	Octave	C1, C2
3:02	7	Perfect Fifth	C1, G
4:03	5	Perfect Fourth	G, C2
5:04	4	Major Third	C1, E
6:05	3	Minor Third	C1, E♭

In equal temperament, the semitone frequencies are calculated as shown in this example from the base pitch of E to F:

$$f_F = \sqrt[12]{2} f_E \tag{2}$$

This frequency relation between semitones creates equal distances between each of the twelve pitches in the octave. The same equation is used between any adjacent semitones.

Instrument design determines the specific semitones available to a player. Three tuning systems commonly used for instruments include the pentatonic, diatonic and chromatic tuning systems.

The diatonic scale is used in Western music and consists of seven notes. For a major scale and beginning with any pitch, the following seven notes are found by increasing the pitch by two major second intervals, a minor second, three more major seconds and a final minor second. This can also be written as do - re - mi - fa - so - la - ti - do.

The chromatic scale consists of all twelve tones found in Western music. Each of these notes has an interval of a minor second.

The standard pentatonic scale is composed of a five note scale. Using any tone as the starting pitch, the following four notes are determined by increasing the pitch by a major second, another major second, a minor third and a final major second. Another way of determining the notes is by taking do - re - mi - so - la, leaving out 'fa' and 'ti'.

2.2 Instruments Incorporated into Quatraphone Design

The quatraphone's sound is based on the bells of the carillon. The keyboard style of playing the quatraphone comes from the piano, while the musical plates that were created are similar to those of a xylophone and glockenspiel. Each of the sections below describes these instruments in more detail.

2.2.1 Carillon

A carillon is a musical instrument traditionally composed of at least 23 cast bronze bells like those shown in Figure 2(a) [2]. These bells are generally found in a tower, such as that of a church tower [3].

The bells are each musically a half step apart and are played from a keyboard, or clavier, made of wood levers and pedals. This is shown in Figure 2(b) [2]. The levers and pedals are connected to the bells through wires and clappers that strike the bell. Some carillons use electronic methods for playing the notes instead of mechanical, though they do not allow for as much musical variation while playing the instrument [3].

(a) Cast bronze bells. (b) Carillon keyboard.

Figure 2: Carillon.

2.2.2 Piano

Unlike a carillon, a piano contains the entire instrument in one unit. As shown in Figure 3 [4], the keyboard and the strings are adjacent to each other.

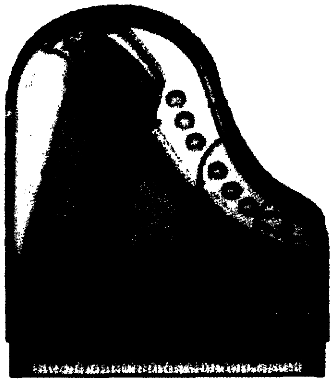


Figure 3: Piano keyboard and strings.

The name piano is short for pianoforte. This word comes from the Italian gravicembalo col piano e forte, which translates directly into harpsichord with soft and loud. The piano's Italian name accurately describes its creation, as it is an instrument evolving from the harpsichord. The harpsichord does not have any dynamic variation. The piano's strings, which are made of steel wire, can be struck with different intensities of forces by felt-covered hammers operated by the musician at the keyboard, creating varying dynamic levels [5].

2.2.3 Xylophone and Glockenspiel

The xylophone and glockenspiel are two instruments that are played with mallets that the musician strikes onto the keys, unlike the piano and carillon, which have mechanical mechanisms that translate the player's movements onto the strings or bells in a different location. Both the xylophone and glockenspiel are classified as percussion instruments. The xylophone, shown in Figure 4 [6], has keys that are made out of wooden bars, and the glockenspiel, shown in Figure 5 [7], has keys that are made out of metal bars. The bars of each instrument are supported at nodal, or nonvibrating, points and are struck with mallets [5].

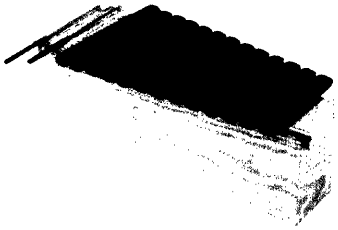


Figure 4: Rosewood xylophone.

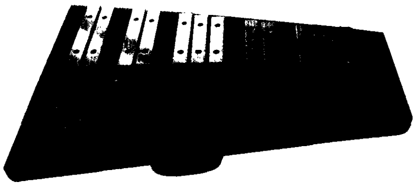


Figure 5: Glockenspiel.

The glockenspiel's origins relate to the carillon. The metal bars used to make the musical tones were originally metal bells. The bars are now arranged in two rows in order through the chromatic scale, relating to the orientation of the white and black keys of a piano. The mallets that hit the metal bars are made of various materials including wood, ebonite and sometimes metal [8].

3 Theoretical Analysis

The theoretical analysis for the quatraphone design consists of theory of the vibration of rectangular plates and damping of vibrations for each plate material.

3.1 Vibration Modes of Rectangular Plates

For the undamped vibration of rectangular plates, the frequency is determined from the material properties and dimensions of the plate as [9]

$$w_{mn} = \pi^2 \left[\frac{m^2}{a^2} + \frac{n^2}{b^2} \right] \sqrt{\frac{D}{\overline{m}}} \,, \quad \text{where} \tag{3}$$

$$D = \frac{Eh^3}{12(1-\nu)} \tag{4}$$

and m and $n = 1, 2, 3,$ are integers that define the vibration mode for the plate, a and b are the side lengths of the plate, is the mass per unit area, E and v are the Young's modulus and Poisson ratio for the plate material, respectively, and h is the plate thickness. For equal side lengths,

$$w_{mn} = \pi^2 \left[\frac{m^2 + b^2}{a^2} \right] \sqrt{\frac{D}{\overline{m}}} \,. \tag{5}$$

Therefore, the frequency for square plates is found to be

$$f_{mn} = \frac{\pi h(m^2 + n^2)}{2a^2} \sqrt{\frac{E}{3\rho(1-\nu^2)}} \,. \tag{6}$$

Note that the geometric dependence is h/a^2, or the ratio of the plate thickness to the side dimension squared. The nodal patterns of clamped square plates for the first three modes are shown below in Figure 6 [10].

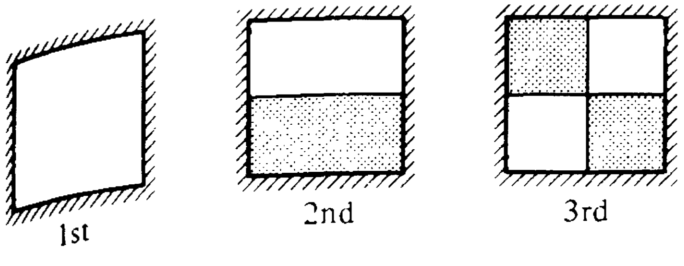


Figure 6: Nodal patterns for clamped plates. 1st mode: (1,1); 2nd mode: (1,2), (2,1); 3rd Mode: (2,2)

For each of the three modes above, the plate vertical displacement $Z(x, y, t)$ as a function of the transverse dimensions x, y and time t are given below, where the frequency f_{mn} is found from Equation 6 and the amplitude of the plate displacement for the (m, n) mode is given by A_{mn}.

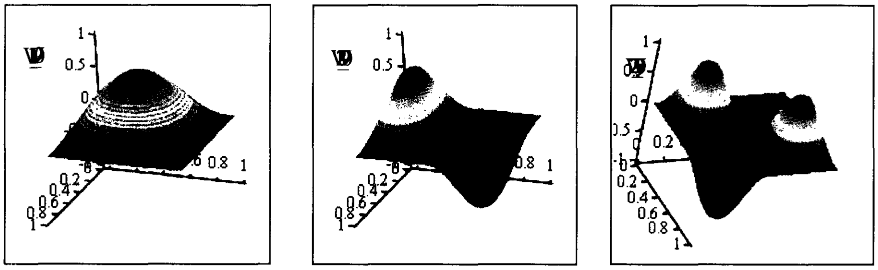
$$
\begin{aligned}
Z_{11}(x,y,t) &= A_{11}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{a}\right)\sin 2\pi f_{11}t && (7)\\
Z_{12}(x,y,t) &= A_{12}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{2\pi y}{a}\right)\sin 2\pi f_{12}t && (8)\\
Z_{22}(x,y,t) &= A_{22}\sin\left(\frac{2\pi x}{a}\right)\sin\left(\frac{2\pi y}{a}\right)\sin 2\pi f_{22}t && (9)
\end{aligned}
$$

Figure 7 shows the 3D models of the plates at one instant in time as they displace during vibration in the first three modes.

All of this theory is based on clamped plates. The vibration nodal patterns are for plates clamped on all four sides as shown in Figure 6 and Figure 7. However, the quatraphone plates are supported at two points on opposite sides from each other, allowing the plates to vibrate more freely. This results in a modification of the mode structure as discussed below.

For the clamped plates, the equations are limited to sine of x and y as shown in equations 7 - 9 so that the edges at $x = 0$, a and $y = 0$, a do not move. The boundary conditions for the quatraphone are different than those of the clamped plates. The quatraphone plates are only held at ($a/2$, 0) and ($a/2$, a), allowing greater movement of the plates during vibration. This introduces cosines of x and y into the equations, and m, n = 0 is now possible. The lowest modes have become (1, 0), (0, 1) and (1, 1) [11].

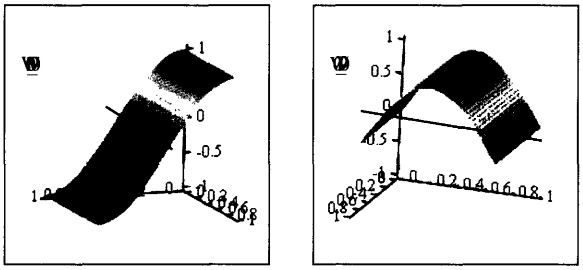
3D models of the additional two modes are shown in Figure 8. Again the 3D models of the plates are at one instant in time as they displace during vibration in each mode.



(a) Mode (1,1)   (b) Mode (1,2)   (c) Mode (2,2)

Figure 7: 3D model of plate vibrations, modes 1–3, with the plates edges held along the x and y axes and the plate vibrating in the z direction.

For each of the two additional modes, the plate vertical displacement $Z(x, y, t)$ that satisfies the boundary conditions at $(a/2, 0)$ and $(a/2, a)$ is given by the following



(a) Mode (1,0) (b) Mode (0,1)

Figure 8: 3D models of plate vibrations in (1, 0) and (0, 1) modes. The plates are held at the edges along their centerline.

equations:

$$Z_{10}(x, y, t) = A_{10} \cos\left(\frac{\pi x}{a}\right) \sin 2\pi f_{10} t \tag{10}$$

where there is no variation in the y-direction, and

$$Z_{01}(x, y, t) = A_{01} \sin\left(\frac{\pi x}{a}\right) \sin 2\pi f_{01} t \tag{11}$$

where there is no variation in the x-direction.

3.2 Vibration Damping of Plates

There are several factors that determine the amount of damping the plates will experience. The main sources of damping in a mechanical system include the energy dissipation of the structural materials, and the dissipation in the joints and contacts between components, for both stationary and moving joints [9]. Therefore, both the selected material and method of holding the plates will affect the damping of the plate's pitch.

For an undamped system, the resonant frequency ω and the natural frequency ω_n are equal to each other. This is possible when the damping ratio ζ goes to zero for the 2nd order system, since

$$\omega = \omega_n \sqrt{(1 - \zeta^2)} \tag{12}$$

The damping coefficient, c, is defined as

$$c = 2\zeta\sqrt{mk} \tag{13}$$

where m is mass and k is the spring constant, or stiffness [12]. In order to minimize the damping coefficient, the factor $\sqrt{mk}$ must be minimized. The stiffness for a beam simply supported on two ends is $k = 3EI/l^3$, where E is Young's Modulus, inertia $I = (wh^3/12)$, and w, l, and h are the beam width, length, and height, respectively.

Therefore, the following quantity must be minimized

$$\sqrt{\frac{EIm}{l^3}} \ . \tag{14}$$

Substituting for I and m in terms of plate dimensions and density, and assuming square plates so that $w = l$, the quantity to be minimized becomes

$$h^2\sqrt{\rho E} \ . \tag{15}$$

From this, the following terms should be minimized for the plate: Young's Modulus, density and height. Table 2 shows the comparison of the Young's Modulus and density for each of the materials. From this comparison, aluminum and brass are shown to have the least amount of damping for a given plate thickness (height). The materials are ordered from least to most damping. Though these factors should be considered to minimize damping of the plates when choosing their material composition, they do not account for the ease of machining, purity of the tone obtained and material costs.

Table 2: Comparison of Material Properties.

Material	E **(Pa)**	ρ **(kg/m^3)**	ρE **(Pa-kg/m^3)**
Aluminum	7.00×10^{10}	2660	1.86×10^{14}
Brass	1.00×10^{11}	8360	8.36×10^{14}
Bronze	1.20×10^{11}	8300	9.96×10^{14}
Stainless Steel	1.95×10^{11}	7640	1.49×10^{15}

4 Experimental Procedure

The quatraphone was developed over three phases: the design phase, the solid modeling phase and the manufacturing phase. In the first phase, the main objective was to determine how to obtain the desired pitches for the quatraphone plates while minimizing the damping of the tones created. In order to achieve this, experimentation included determining the damping of different materials and mounting methods. The plate resonance frequency was also measured for different plate dimensions and materials.

In the solid modeling phase, solid models and drawings were created for each component of the quatraphone. SolidWorks was used for the modeling and assembly of all the parts. Following the modeling phase, the quatraphone was manufactured by machining and assembling each of the instrument's components. The following sections provide details into the methods and apparatus used for each phase of the quatraphone's development.

4.1 The Design Phase

In order to determine sound quality, experiments were performed to measure pitch purity, frequency and damping. The tones created by the plates depend on numerous variables. In addition to plate material and dimensions, the sound quality also depends on how the plates are held, where they are struck and the material of the striker. The following sections will describe the apparatus and methods to characterize the plate vibrations in order to determine the ideal conditions for the quatraphone plates.

4.1.1 Damping

The first stages of development for the quatraphone were to determine the material, as well as how to hold and strike the plates. Equation 6 was useful when considering which material to use for making the plates. Stainless steel, brass, bronze and aluminum were used in testing.

The tone purity (i.e. number of harmonics), tone frequency (frequency of the highest amplitude harmonic) and damping of the tone were tested with the following variables: rectangular keys, square keys; striking the plate in the center, striking the plate on the edge; striking the plate with a mallet made of rubber, wood, metal, plastic; holding the plate with electrical wire, rubber bands, string; holding the plate with a one, two and three point support system.

4.1.2 Frequency

While determining how to make the plates with specific pitches for the instrument, Sound Recorder, Vernier Logger Pro and MathCAD software were used to determine the frequency and damping of the obtained tones. A microphone was placed next to the plates. When the plates were struck with a mallet, the sound was either recorded with Sound Recorder or read directly into the Vernier Logger Pro software. This software generated the Fast Fourier Transform (FFT) of the waveforms, showing the spectrum of the waveforms and the location of the peak frequencies.

Opening the Sound Recorder files of the tones in the Mathcad program SoundAnalysis.mcd [13] also showed the waveforms produced by the plates, the FFT of the tones and the damping of each of the pitches. This data analysis determined which materials created the most resonant tones at the desired pitches.

Based on the purity of the tones, as measured from the FFT of the recorded sound, and what sounded pleasing to the ear, it was determined which material was best for specific ranges of frequencies. For each material the frequency of the tone was plotted against the thickness over the side length squared. The best fit line of these curves provided an experimentally obtained equation for determining the length of each key for a desired frequency and a given thickness (Equation 6).

The number of keys and pitch of the keys was decided by considering the possible tuning systems and the desired range for the quatraphone prototype. From that information it was possible to compose a short piece for the quatraphone based on the available notes.

4.2 The Solid Modeling Phase

The final stages of development involved designing a lever mechanism for holding the keys, striking them, and setting them up next to one another considering their varying sizes. Simplicity of manufacturing, ease of assembly, cost of materials, minimizing the instrument's size and ease of playing the instrument each had an affect on the final design. A mockup of the lever mechanism for a single key was created and tested before finalizing the design of the quatraphone.

4.3 The Manufacturing Phase

Several machines available in the Pappalardo Lab at MIT were used to construct the quatraphone, including the mill, lathe and waterjet. A table specifying which machines were used and their make and model numbers are shown in Table 3.

Table 3: Make and model numbers for machines used for manufacturing.

Machine	**Make, Model Number**
Bandsaw	Dake, Parma Trade Master
Drill Press	Delta, Taladradora de 254 mm
Lathe	Bridgeport, Tormax 13.5
Mill	Bridgeport/EZTrak
Tap	Wilton
Waterjet	OMAX 2626

5 Results and Discussion

This section details the various stages of the quatraphone design process. Discussion includes the specific parameters found for the quatraphone plates in order to create the best tone. Additionally the quatraphone lever design, as well as the manufacture of the instrument, is described throughout the following sections.

5.1 The Plates

This section describes how decisions were made about how to hold the plates, what material to use for holding them, the shape and size of the plates, where to strike them, what material to use for striking them and the choice of the tuning system.

The plates were initially cut into various sized rectangles. Without using the recording and analysis software, it was obvious that multiple tones were being created when striking the plates. After further research, it was determined that xylophones with rectangular plates have a concave cut in the bottom of the plate in order to eliminate unintended frequencies. The plate design changed to square plates, which eliminated the undesired tones that usually created dissonance. This is further understood by considering Equation 8 which shows that the frequency for a square plate is the same in both the (2, 1) and (1, 2) modes.

In order to test further design parameters for the plates, it was necessary to decide how to hold them, allowing for the best tone. String was eliminated since it was not able to hold the plates with enough stability to strike them multiple times in a short period of time. Rubber bands were tested since it was believed they could hold the plates at three points, as shown in Figure 9, and still allow the tone to resonate as desired. This hypothesis was not correct, and the rubber bands quickly damped the

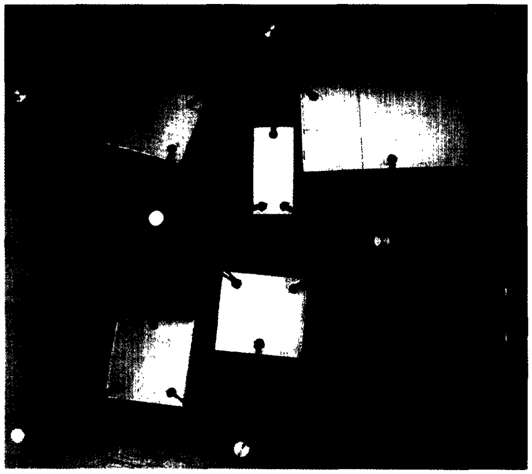


Figure 9: Rubber band support system.

tone after the plates were struck. Electrical wire was tested in order to have a stable support system and only hold the plates at two points. As shown in Figure 10, the wire held the plates on opposite sides, in the center of the plate, and it was twisted in opposite directions to prevent the plate from "unwinding" when struck by the mallet. This system worked well, allowing the tone to resonate and creating a stable support system. A lower gauge wire was required for the smaller plates with correspondingly higher tones. While each of the square plates of steel, brass, bronze and aluminum were tested for tone purity, frequency compared to size and damping of the tone, it was also determined whether or not their pitches were appealing to the naked ear. Graphs such as the one shown in Figure 11 were analyzed for each of the materials.

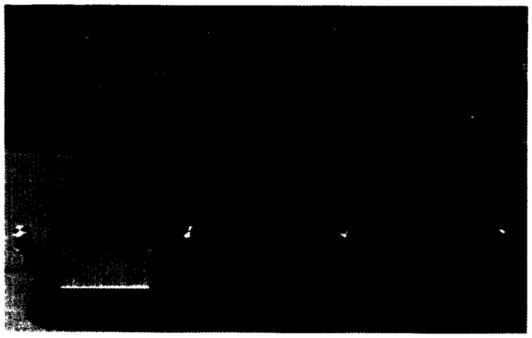


Figure 10: Electrical wire support system.

As shown in Figure 11 [13], the brass had one large peak frequency. It also had a significant resonant time, making it one of the materials selected for use in the quatraphone. The brass produced the best tones in the lower range of the desired pitches for the instrument. It was found that the brass plates must be struck in the center in order to produce the purest and least damped tone. Aluminum was selected as the material for the higher pitched notes of the quatraphone due to the same results the brass experienced in the lower range, as shown in Figure 12 [13]. However, aluminum must be struck in the corner in order to produce the best tone.

Bronze produced several peak frequencies, shown in Figure 13 [13]. The multiple frequencies of the bronze eliminated it from selection for use the quatraphone. The steel did not resonate as well as did the aluminum and brass and is the most difficult of the materials to machine. Therefore, steel was also eliminated from further testing.

Table 4 shows the comparative damping of each of the materials that were discussed above. The time of decay is the amount of time it took the amplitude to decrease to half of its initial value.

The table presents ρE for comparison to Table 2 from the theory section. Other than for bronze, the materials follow expected values. This may occur due to how the plate

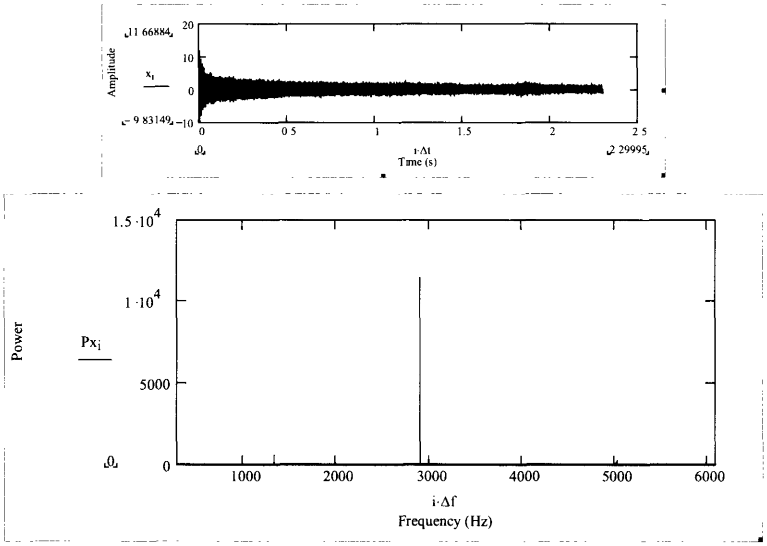


Figure 11: Brass waveform and peak frequency.

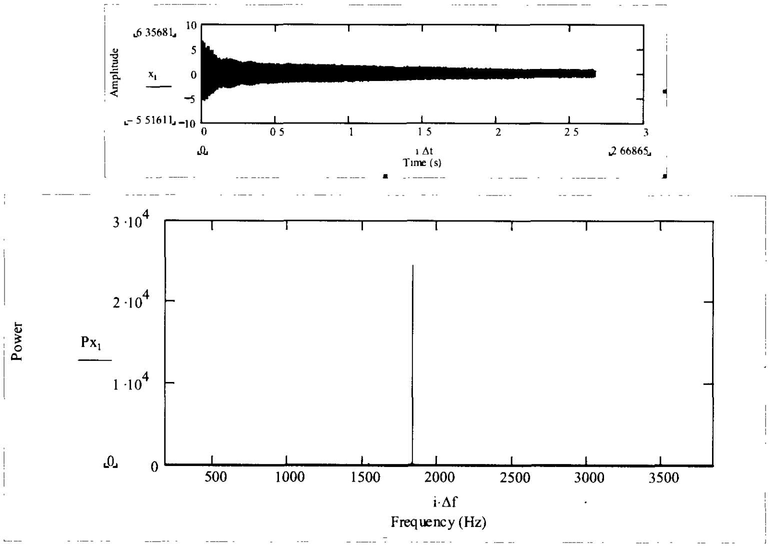


Figure 12: Aluminum waveform and peak frequency.

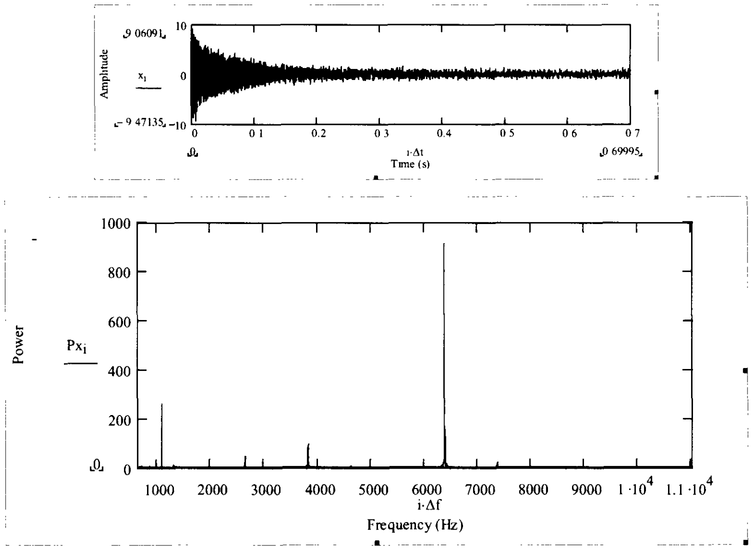


Figure 13: Bronze waveform and peak frequency.

Table 4: Decay time for each material.

Material	**Time (sec)**	ρE **(Pa-kg/m^3)**
Aluminum	2.25	1.86E+14
Brass	1.25	8.36E+14
Bronze	0.07	9.96E+14
Stainless Steel	0.2	1.49E+15

is struck during testing. In order to determine the specific size of each plate for the desired tones, the resultant frequencies acquired from each of the sample plates were graphed verses thickness of the plate over its side length squared ($1/m$), as shown in Figure 14. A best fit line is also shown with the data.

The equations for the brass and aluminum best fit lines were found to be:

$$f_{Brass} = 13.543a + 14.515 \tag{16}$$

$$f_{Alum} = 19.886a + 107.84\ . \tag{17}$$

From the experimental data obtained and shown in the above figures, it was possible to calculate the exact size each plate should be for its desired frequency. The plates were cut on the waterjet based on these calculated values. The frequencies were sampled to ensure the correct values, and the sizes of the plates were adjusted slightly on the mill when necessary.

Figure 15 shows the experimental data graphed against the theoretical values which

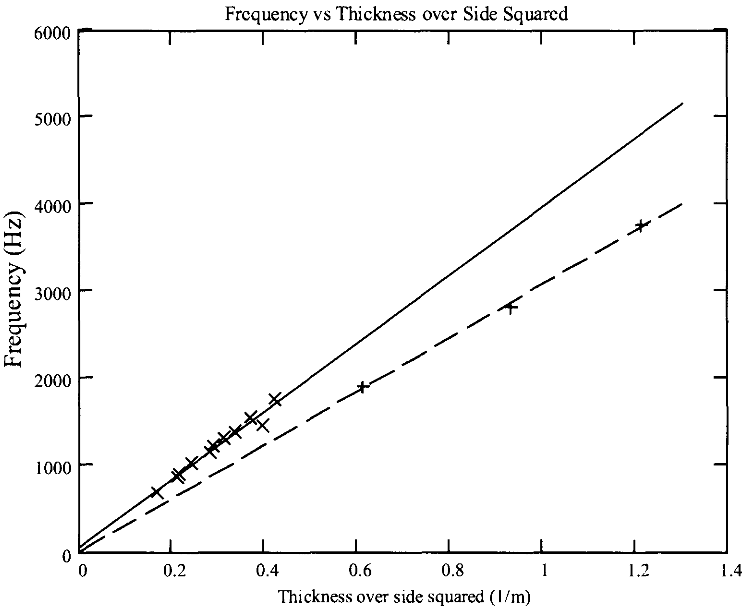


Figure 14: Experimental data and best fit lines. xx Measured Brass Frequency, – Brass Best Fit Line, ++ Measured Aluminum Frequency, - -Aluminum Best Fit Line

helped determine the mode in which the plates were vibrating. The brass plates vibrate in the (1, 1) mode, which explains why they must be struck in the center to produce the purest tone, while held at ($a/2$, 0) and ($a/2$, a). This is visually explained with the graph of the (1, 1) mode vibrations in Figure 7. The aluminum plates vibrate in the (1, 0) modes, requiring them to be struck in the corner to obtain a pure tone, while supported in the same place as the brass at (a/2, 0) and (a/2, a). This is also shown in the graph of the (1, 0) mode vibrations in Figure 8.

The brass and aluminum experimental values were found with 6% and 12% error respectively as compared to their theoretical values. This error is mostly created due to the less than ideal holding method for the plates. The actual method is not the exact same as modeled with the theoretical values.

Additionally, it was observed that the plates must be struck quickly, not allowing the mallet to rest on them; otherwise it will quickly damp the tone of the plate. The problem was first solved by holding onto plastic tubing on the end of the mallet, to allow the mallet to bounce of the plate once it was struck. This is shown in Figure 16.

The permanent solution to ensure the mallet struck the plate quickly was the use of springs in the final design of the quatraphone.The mallet heads were tested with rubber, metal, wood and plastic. The rubber head could not produce a loud enough tone. The metal head created additional noise when striking against the metal plate.

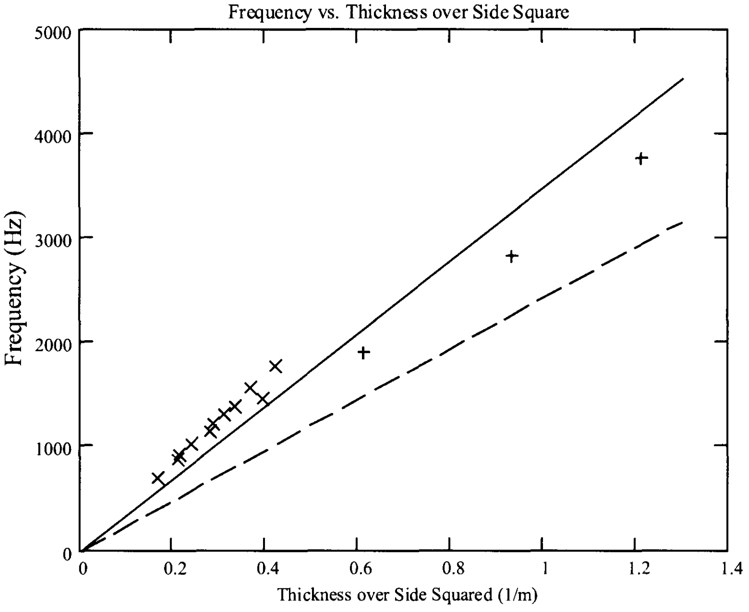


Figure 15: Experimental data with theoretical values. xx Measured Brass Frequency, – Theoretical Brass (1,1) Mode, ++ Measured Aluminum Frequency, - - Theoretical Aluminum (1,0) Mode

The wood head was hard enough to create a significant tone volume and created a more vibrant tone than did the plastic head. Therefore the wood mallet head was used in the final design.

5.2 Quatraphone Design

The quatraphone design went through multiple stages. Initially, a sample plate was used to create a mockup of a single key assembly. After the mockup was created and tested, a full assembly was designed for the fourteen key system, which was then constructed.

The tuning system for the quatraphone was chosen to be chromatic in order to allow the musician to play a wide range of music. The prototype was made of fourteen notes, mostly in a single scale, $B\flat$ major, to allow the musician to play in a single key. Beyond the base eight tones, several tones were added to allow for use of several lower pedal tones as well as modulation to the dominant key of the root scale. The notes available on this model of the quatraphone are shown on the piano keyboard in Figure 17. The available notes are also shown on the treble clef staff in Figure 18. The quatraphone design evolved throughout the testing process, adapting to each of the results found that affected the plate design. A mockup assembly was created that incorporated the following factors: plate shape and size, plate support system, mallet

Figure 16: Mallets with and without plastic tubing.

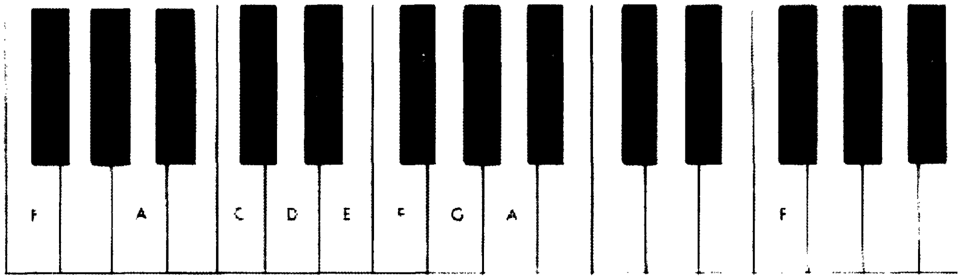


Figure 17: Pitches of the quatraphone on a keyboard.

structure, placement of mallet strike. In addition to the specific results obtained in earlier experiments, the quatraphone design had to integrate the design requirements of the musician playing the instrument, including the placement of the keys for ease of access and a logical order so that the musician can find the notes. Other goals of the design included a condensed assembly that could easily be disassembled for ease of repair.

All the above goals were brought together and tested in a mockup of the expected quatraphone assembly. The mockup of a single key system is shown in Figure 19 with each of the parts labeled. This design shows all the components that were incorporated into the quatraphone's lever mechanism design for the aluminum plates. A similar design was required for the brass plates, but the placement of the mallet was in the center of the key instead of on the edge. In the final design, the lever itself was fabricated from a single aluminum piece cut to shape with a key at the end for the musician to strike. The lever pivots through a single pin, held to the pivot block. On the opposite end from the musician, the striker is attached with a spring pin. On this same end of the lever, a spring is hooked to the bottom of the striker in order to ensure the lever returns to its resting position after the striker strikes the key. A picture of the final lever mechanism assembly is shown in Figure 20.

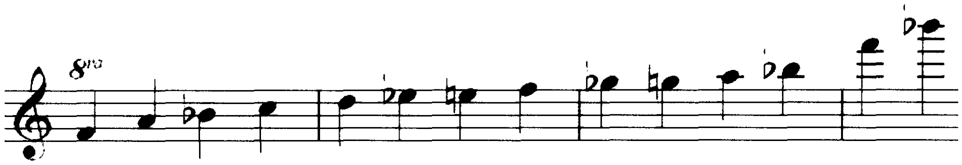



Figure 18: Pitches of the quatraphone on a staff.

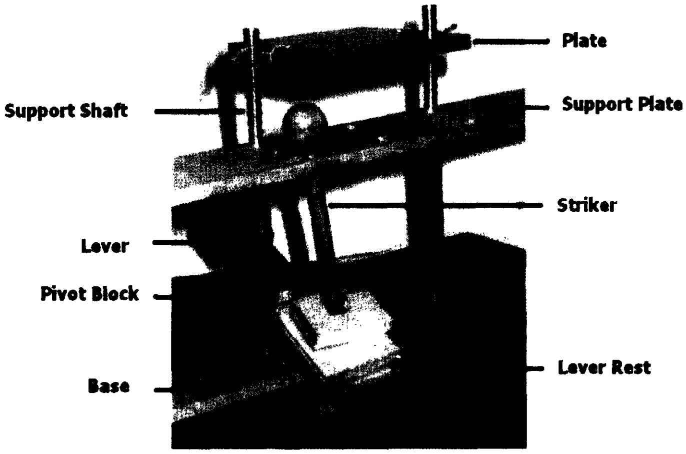


Figure 19: Mockup of single key system.

After testing the mockup and proving the design created the desired sound, solid models were created for the full assembly of the quatraphone before beginning manufacturing of the parts. Throughout the full assembly design process, the number of unique parts was minimized to ensure the simplest possible manufacturing process.

A list of parts and what machines were used for each one is shown in Table 5. The aluminum plates created the most number of unique parts even though there were only three of them. The unique parts were necessary since the aluminum plates are struck on their corner edge, which has a different location depending on the plate size. The brass plates were consistent since they are struck in the center, which is always in the same location for every plate size.

The final solid model of the quatraphone assembly is shown in Figure 21, and the individual parts drawings are included in the Appendices.

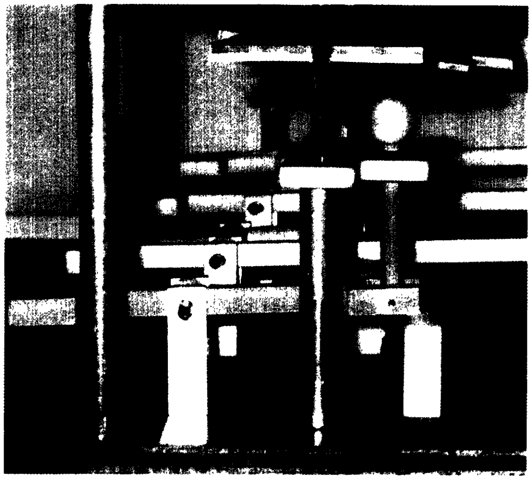


Figure 20: Close up of lever mechanism.

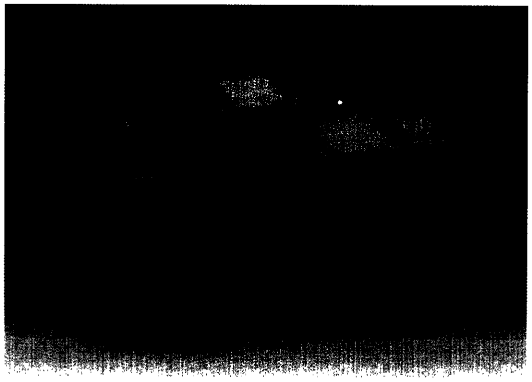


Figure 21: Full assembly solid model.

5.3 Quatraphone Construction

After completing the solid modeling, each piece was manufactured and assembled. The final instrument is shown in Figure 22. After construction and assembly, final adjustments were made on the prototype to minimize extra noise. The noise was coming from movement of the levers in the lever blocks and the levers hitting the lever rests. Plastic spacers and washers eliminated the noise in the lever blocks, and foam pads on the lever rests reduced noise from the levers hitting them after striking the plates.

Future developments on the quatraphone design include making a more extensive version with more than the fourteen notes available in the prototype design. Ideally, all the chromatic pitches in multiple octaves would be available to the musician.

Table 5: Quatraphone parts list.

Part	Material	Machines	Number
Plates - different sizes	Brass	Waterjet, Mill	11
	Aluminum		3
Striker	Wood	Bandsaw, Lathe, Drill Press	14
Support Plate Front	Delrin	Waterjet	2
Support Plate Back	Delrin	Waterjet	1
Support Plate Back Top	Delrin	Waterjet	1
Pivot Block	Aluminum	Waterjet, Mill, Tap	7
Lever Rest	Delrin	Bandsaw, Mill, Tap	7
Lever Small	Aluminum	Waterjet, Mill	6
Lever Medium	Aluminum	Waterjet, Mill	2
Lever Medium 2	Aluminum	Waterjet, Mill	1
Lever Large	Aluminum	Waterjet, Mill	5
Connecting Shaft	Aluminum	Bandsaw, Lathe, Tap	4
Support Shaft	Aluminum, Steel	Bandsaw, Lathe, Tap	18
Base Plate	Wood	Waterjet	1
Base Plate Top	Wood	Waterjet	1

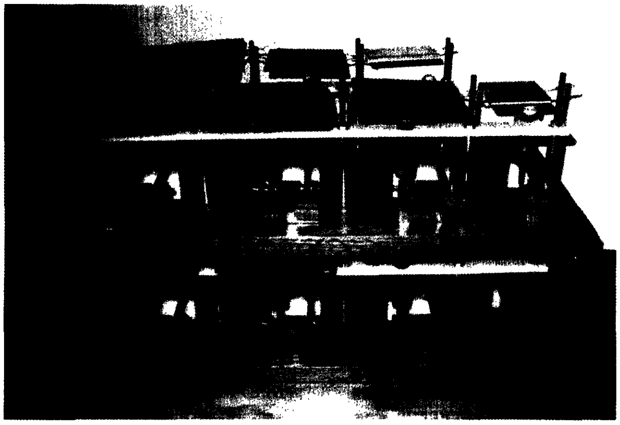


Figure 22: Fully assembled quatraphone.

6 Quatraphone Composition

Following the completion of the quatraphone construction, a short piece of music was composed for the new instrument. This piece uses all fourteen notes of the quatraphone at least once but usually multiple times. Additionally, the end of the piece demonstrates the instrument's ability to play multiple notes at the same time. With the addition of notes to the instrument in the future, a player will be able to produce greater numbers of notes at the same time. The copy of the composition, *Prelude*, is included in the Appendices. A recording of *Prelude* is also attached to this document.

7 Summary

The details of the design for this new instrument, the quatraphone, show the amount of mechanical engineering and musical skill that are required for the design and construction of a usable musical instrument. It is now evident how the quatraphone incorporates various elements of existing instruments.

At first glance, the arrangement of the plates may resemble the placement of keys from a xylophone or glockenspiel. The bell like quality of the notes played by the quatraphone suggests those of a carillon, and the musician recognizes the keyboard qualities of the piano. The musician also responds to the comfort and accuracy of the instrument, while the listener decides if the music is pleasing. The quatraphone is another addition to the world of musical instrument design, and *Prelude* is the first piece that uses the quatraphone's ability to produce pleasing music.

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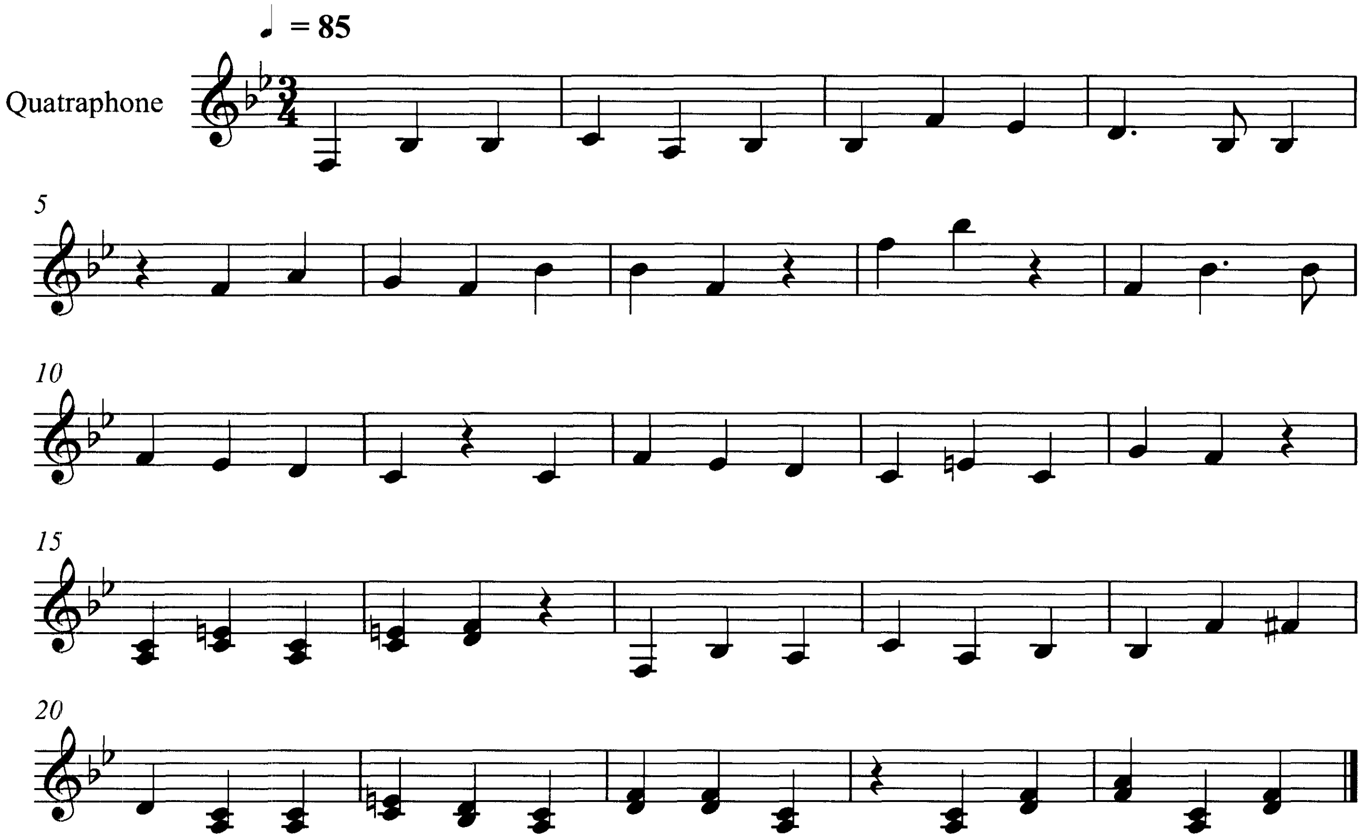
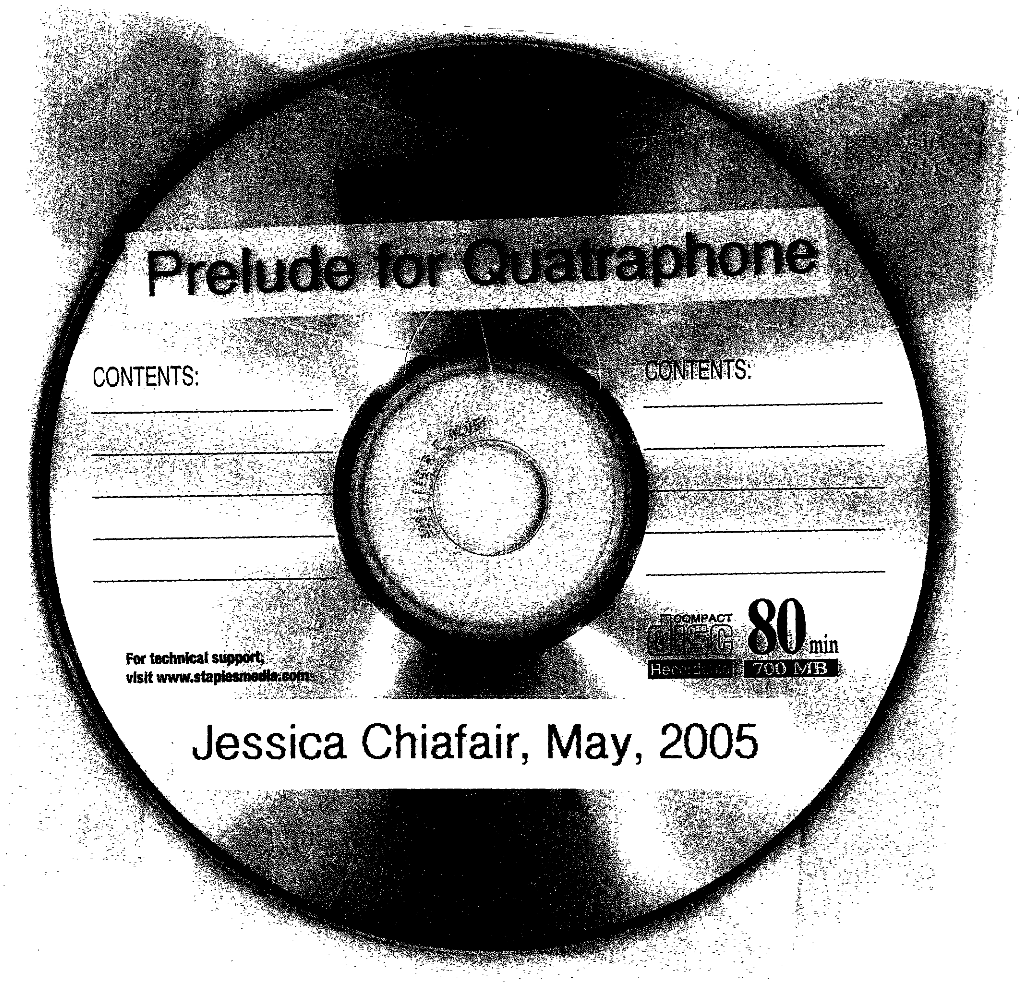
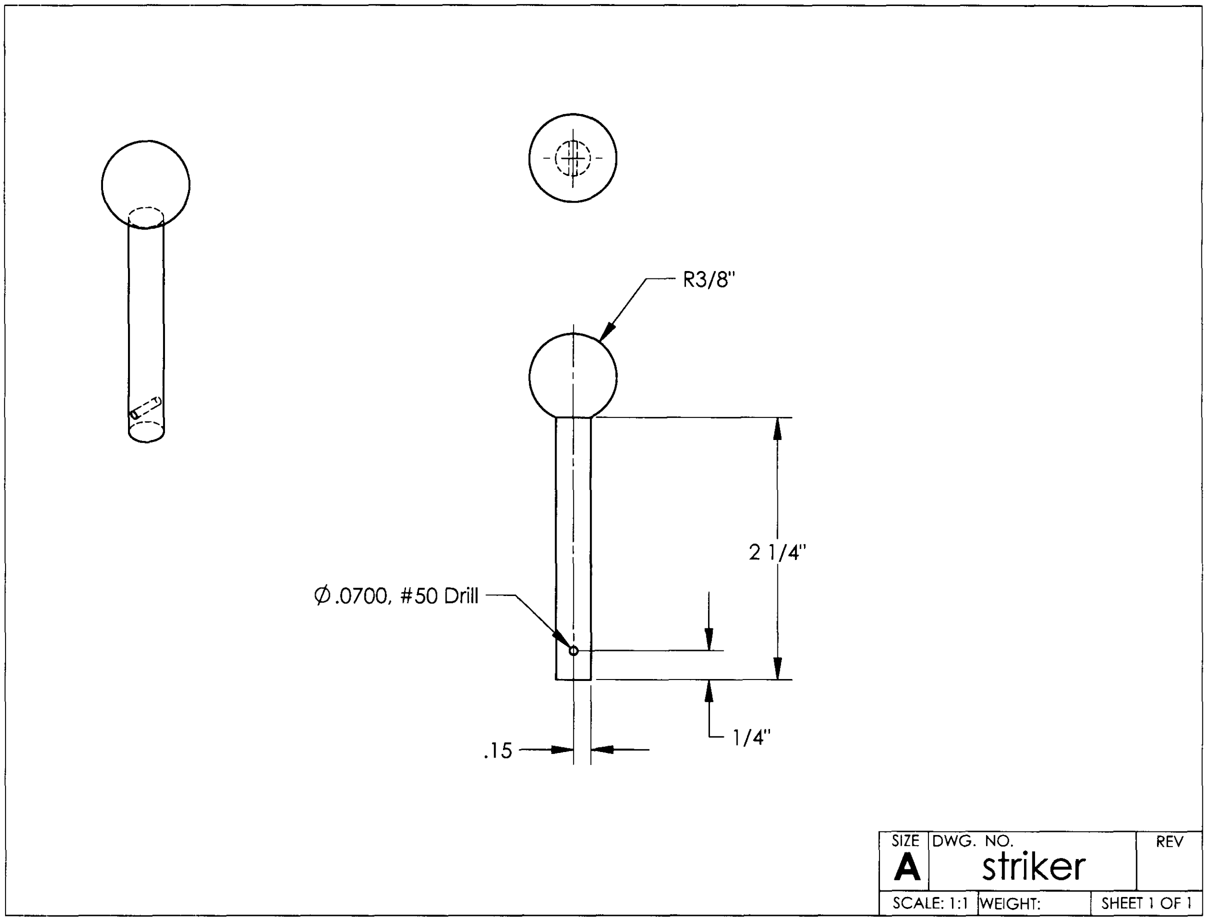
Prelude

Jessica Chiafair

B *Prelude* Recording



C Part Drawings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∅.0700, #50 Drill
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1/4"
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striker
REV
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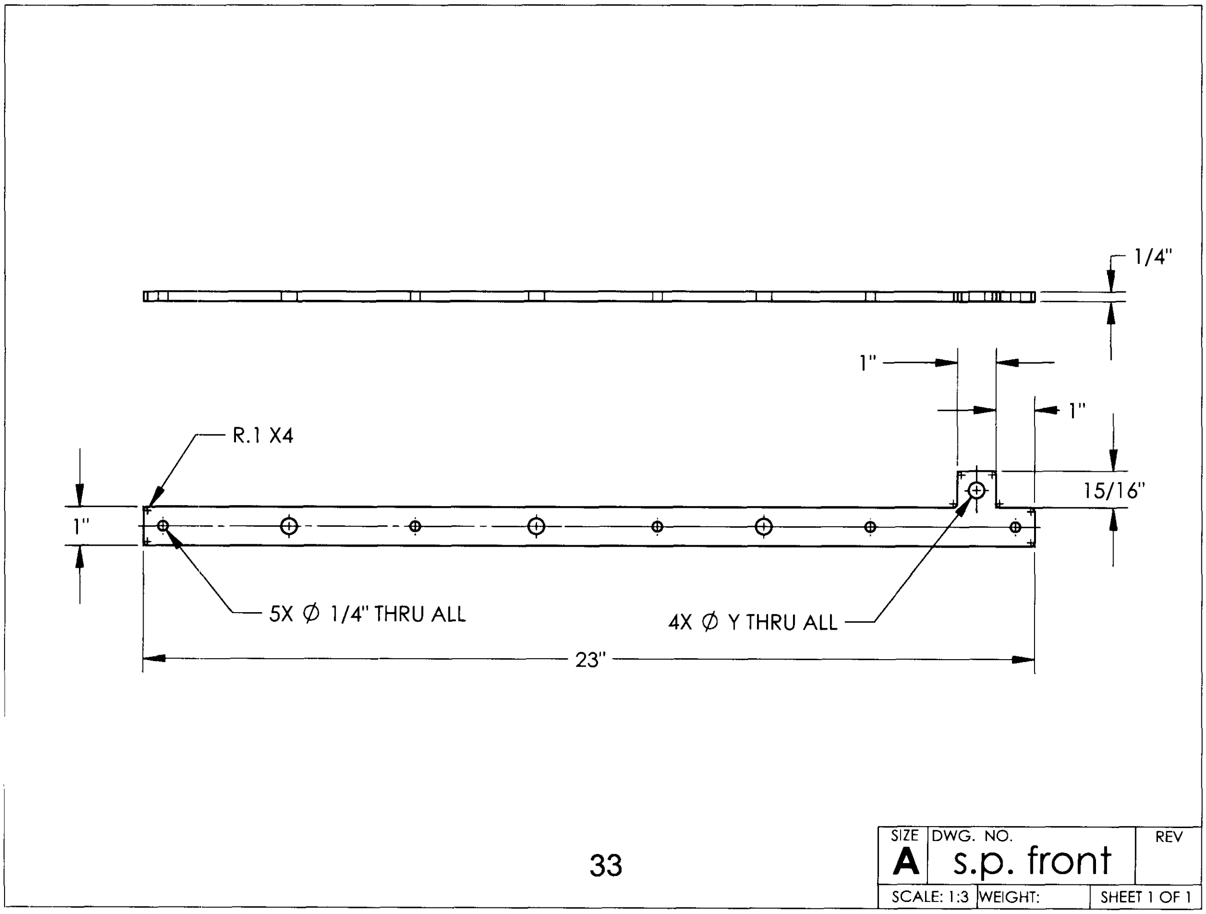
WEIGHT:
SHEET 1 OF 1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1"
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15/16"
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4X ∅ Y THRU ALL
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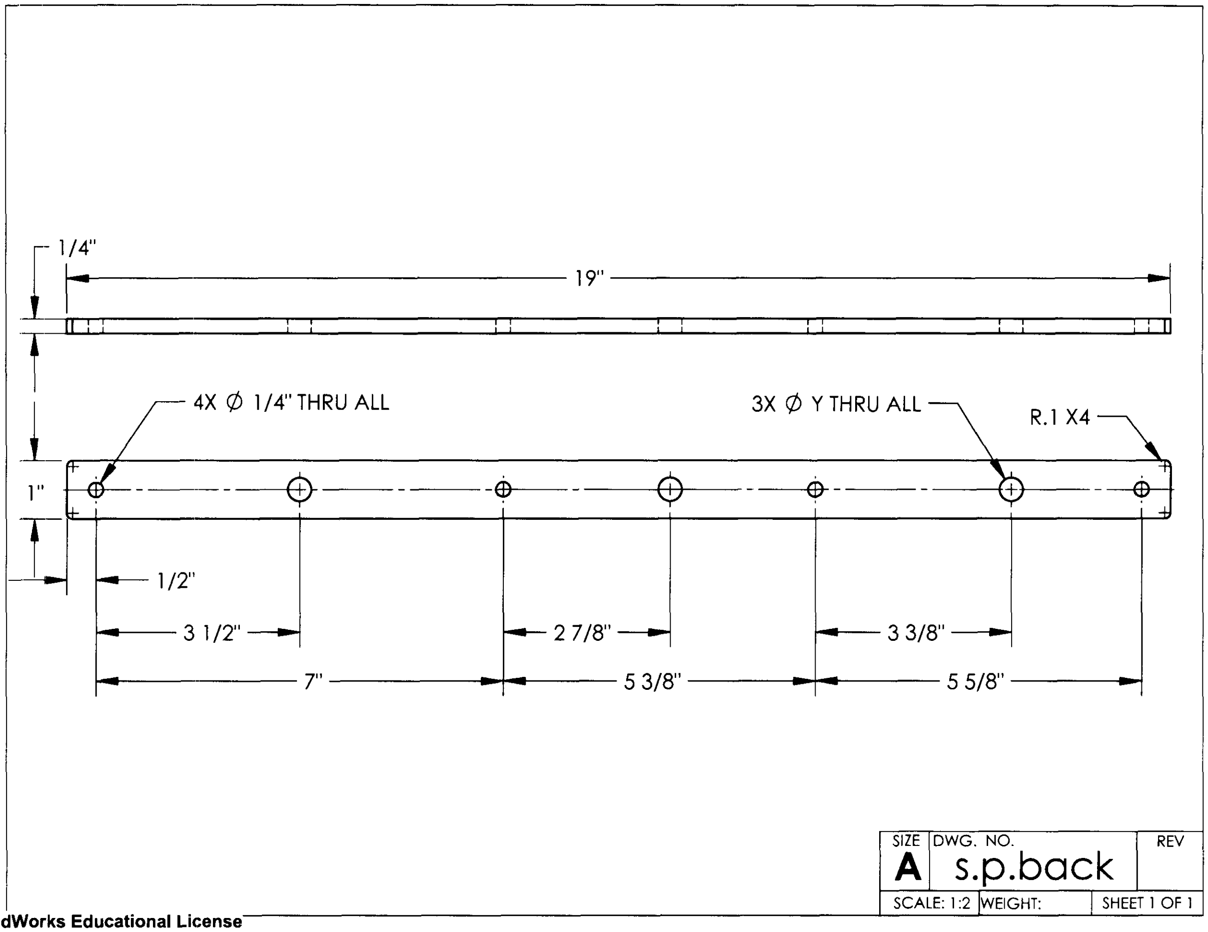
s.p. front
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1



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3X ∅ Y THRU ALL
R.1 X4
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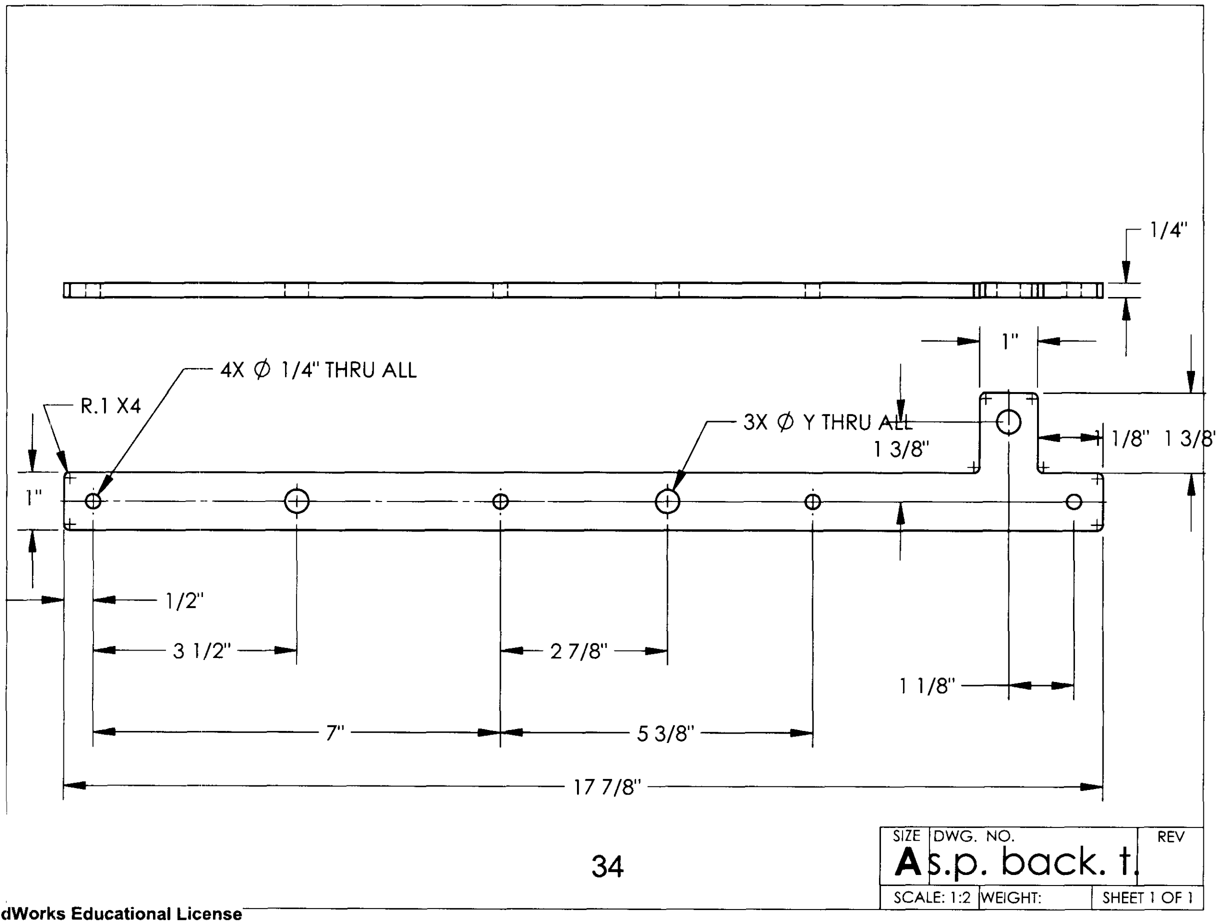
1/2"
3 1/2"
2 7/8"
3 3/8"
7"
5 3/8"
5 5/8"
SIZE
A
DWG. NO.
s.p.back
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



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3X ∅ Y THRU ALL
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1"
1/2"
3 1/2"
2 7/8"
1 1/8"
7"
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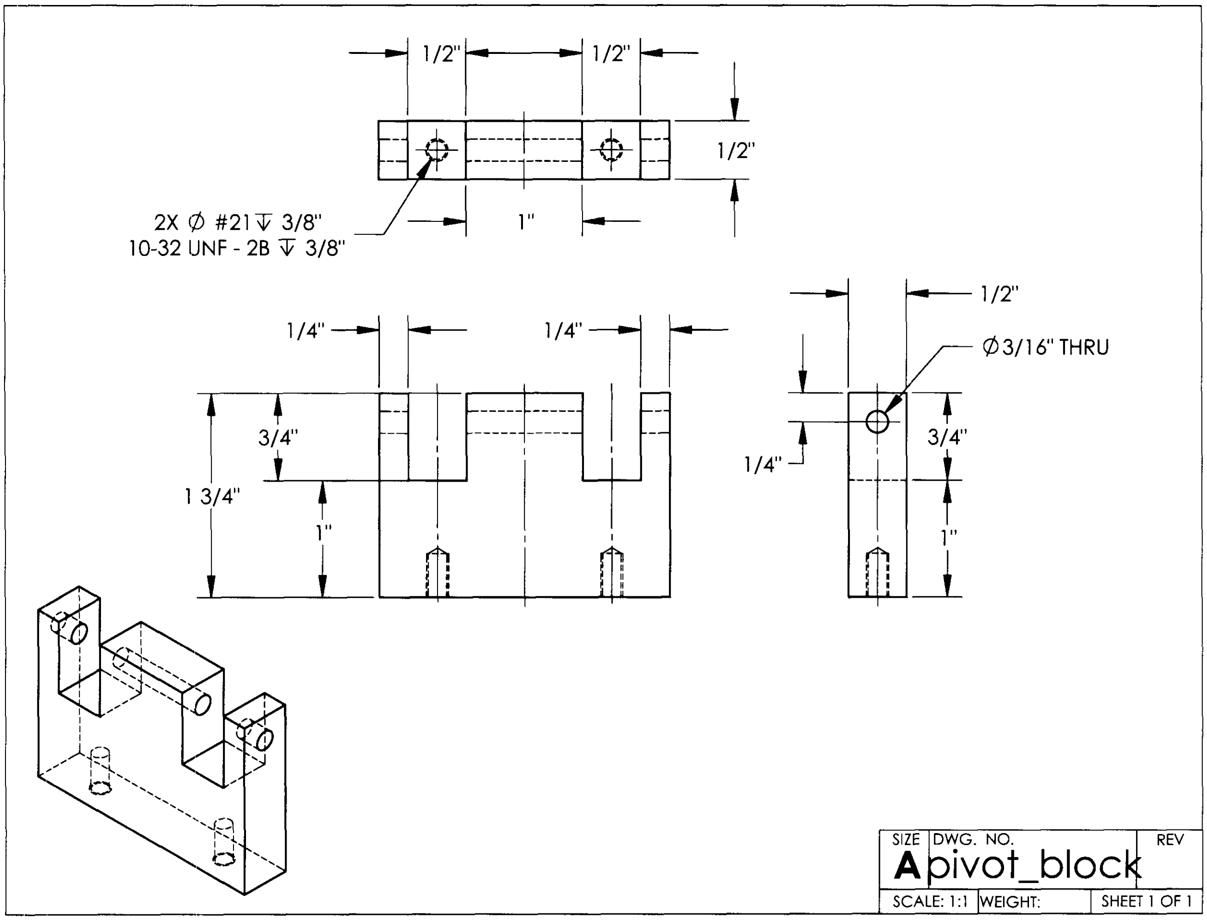
DWG. NO.
s.p. back. t
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1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1/4"
1/2"
⌀3/16" THRU
3/4"
1 3/4"
1"
1/4"
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1"
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REV
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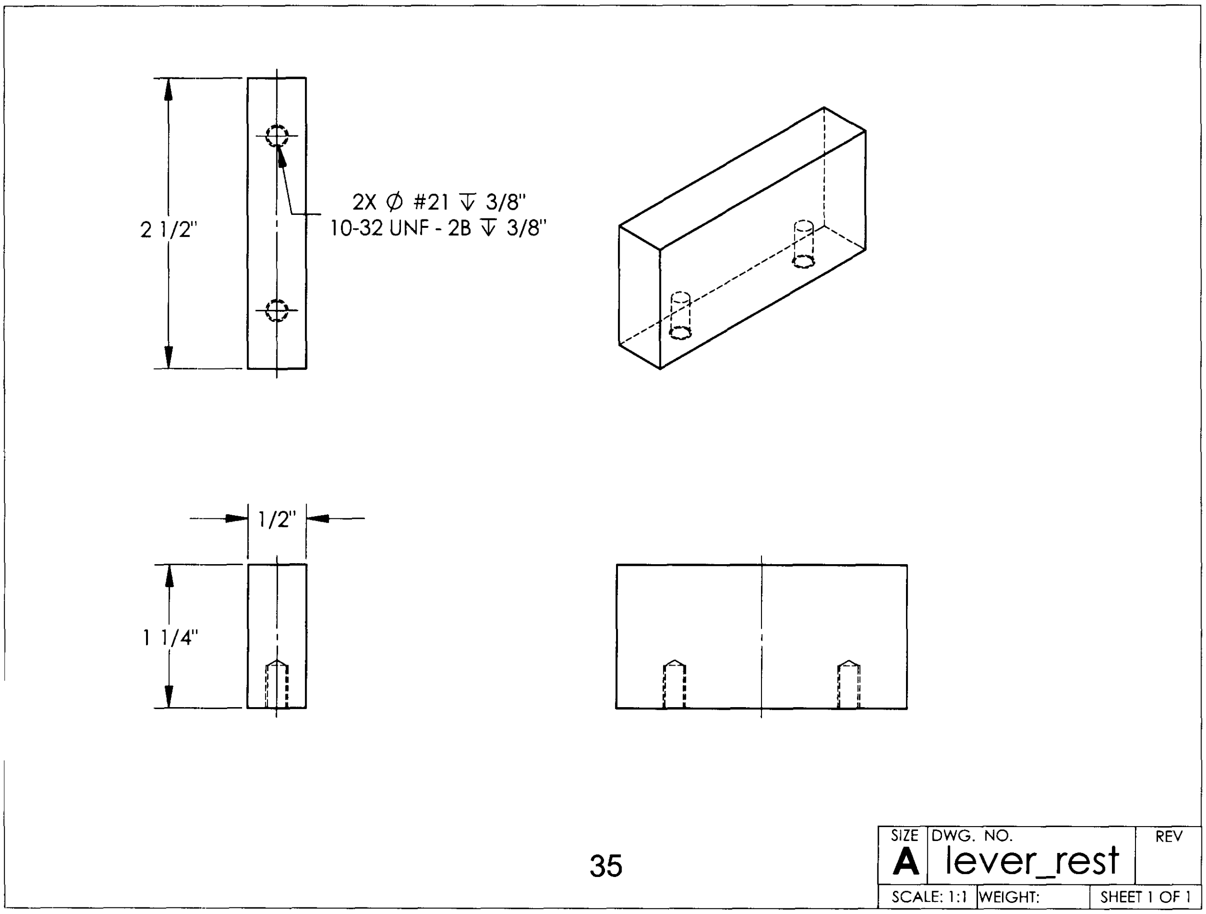
WEIGHT:
SHEET 1 OF 1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REV
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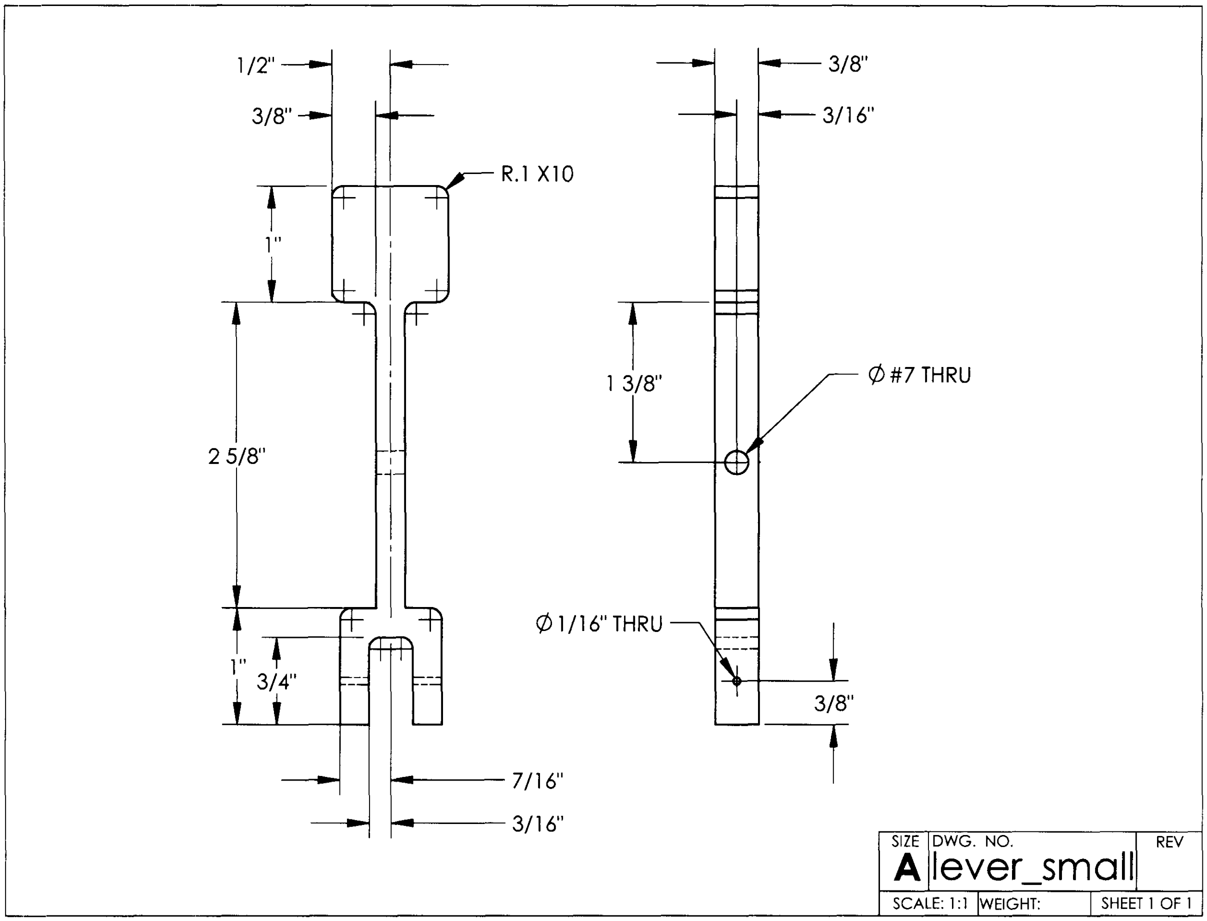
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3/16"
R.1 X10
1"
2 5/8"
1 3/8"
Ø #7 THRU
Ø 1/16" THRU
1"
3/4"
3/8"
7/16"
3/16"
SIZE
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DWG. NO.
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REV
SCALE: 1:1
WEIGHT:
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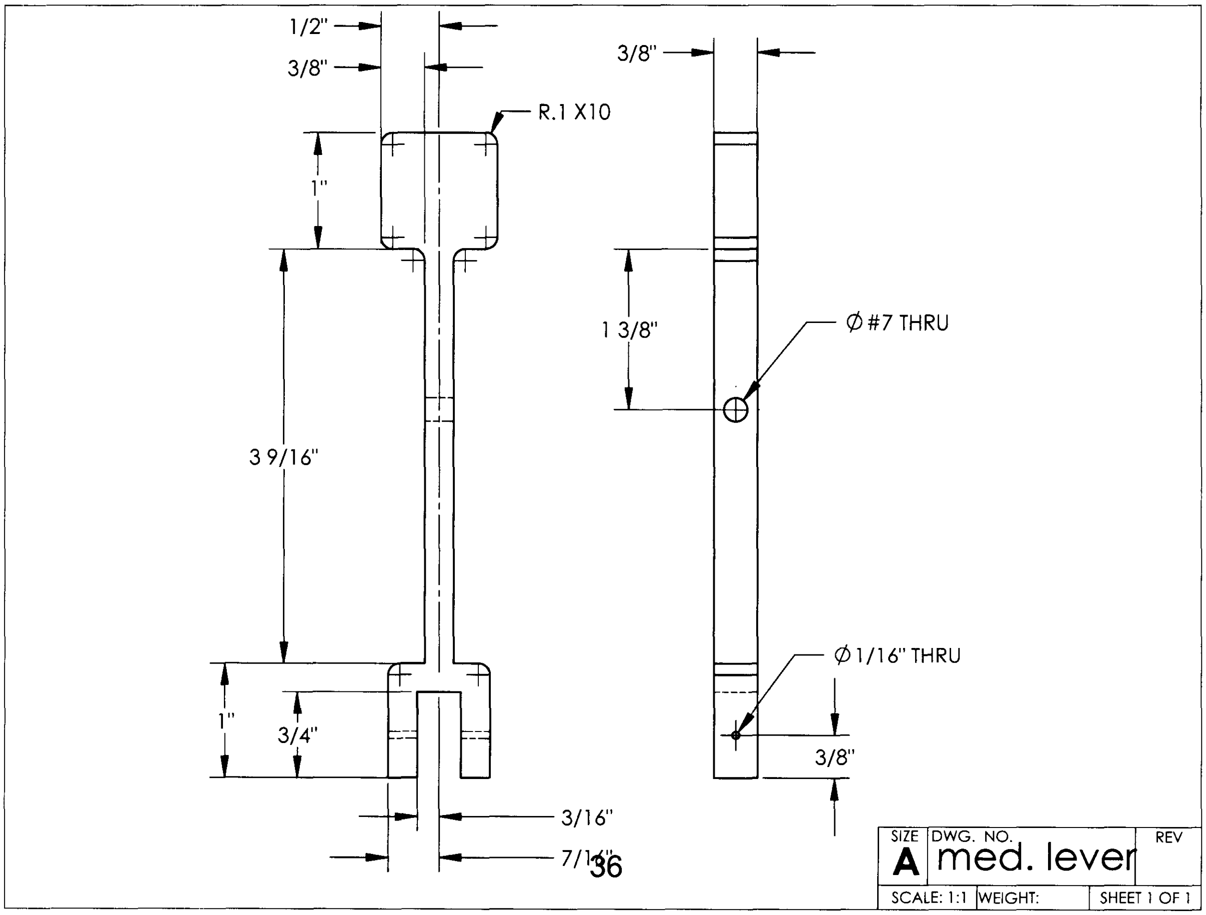
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3/4"
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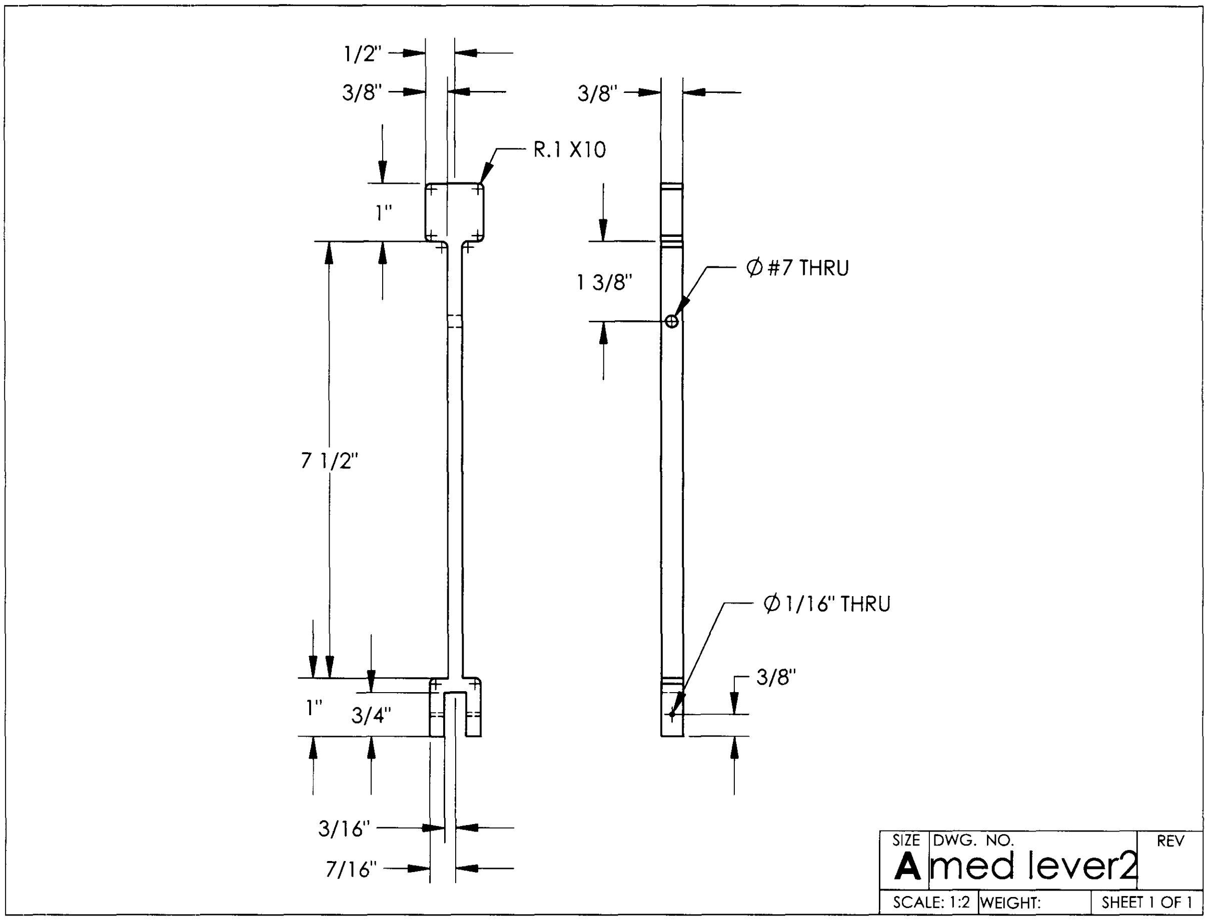
SHEET 1 OF 1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REV
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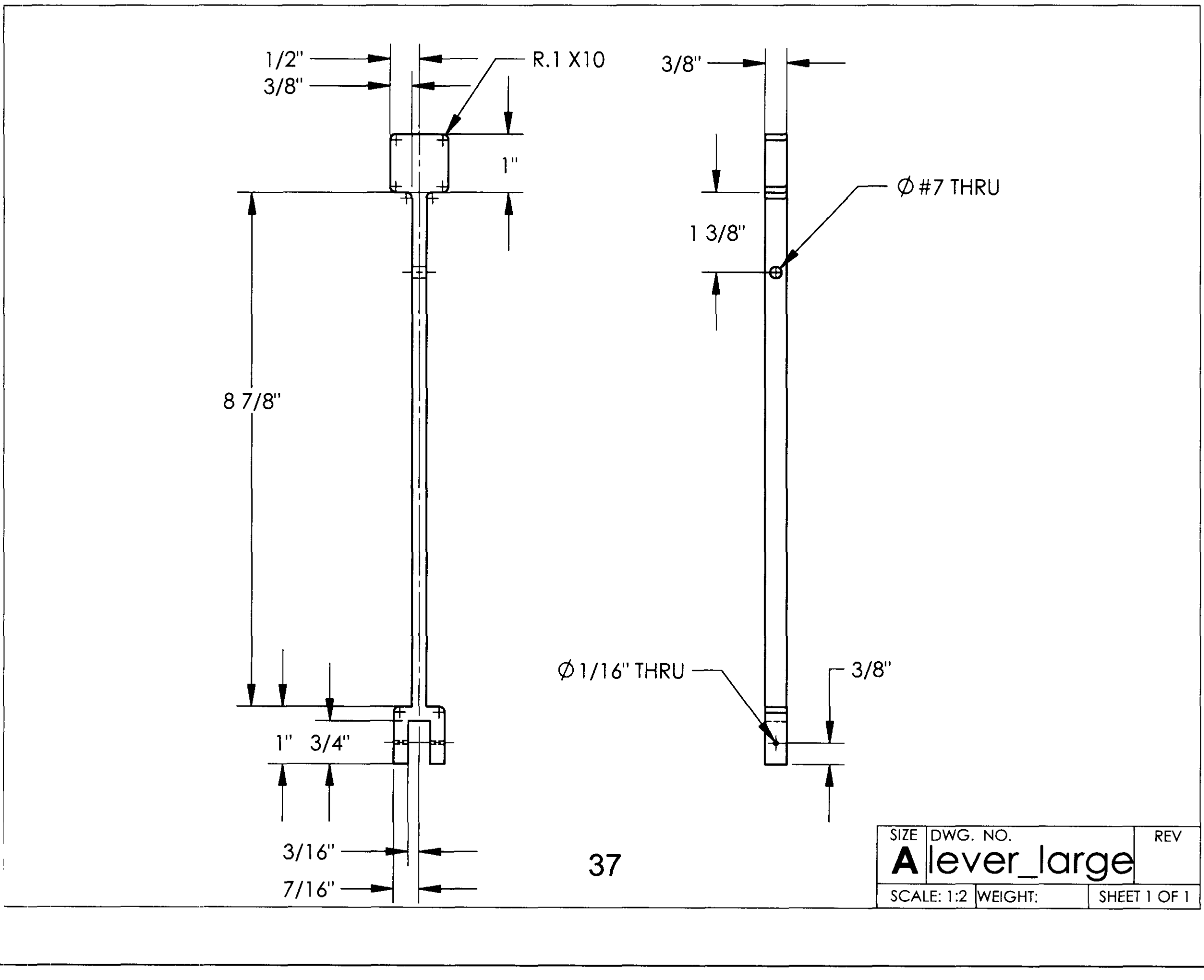
SHEET 1 OF 1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1"
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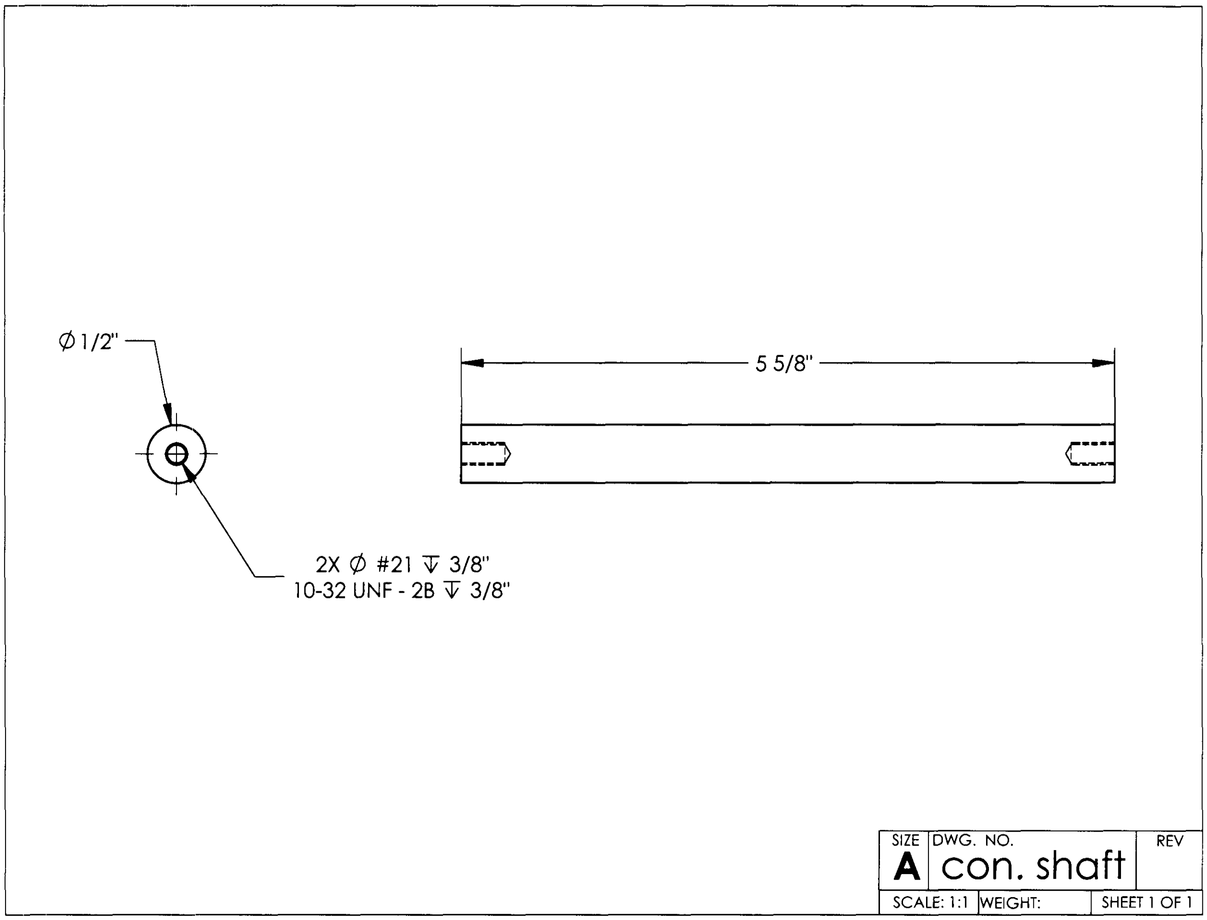
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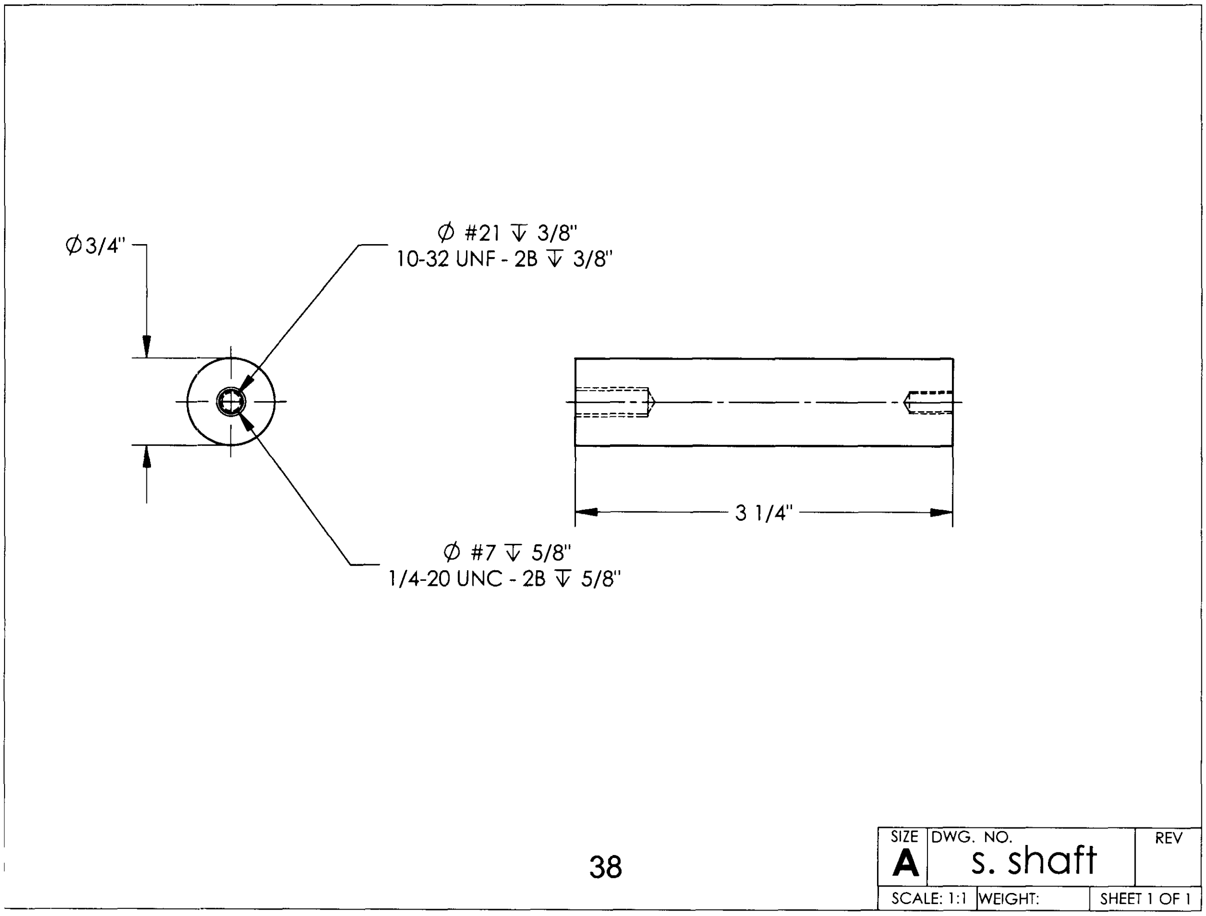
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1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3 1/4"
Ø #7 ↧ 5/8"
1/4-20 UNC - 2B ↧ 5/8"
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REV
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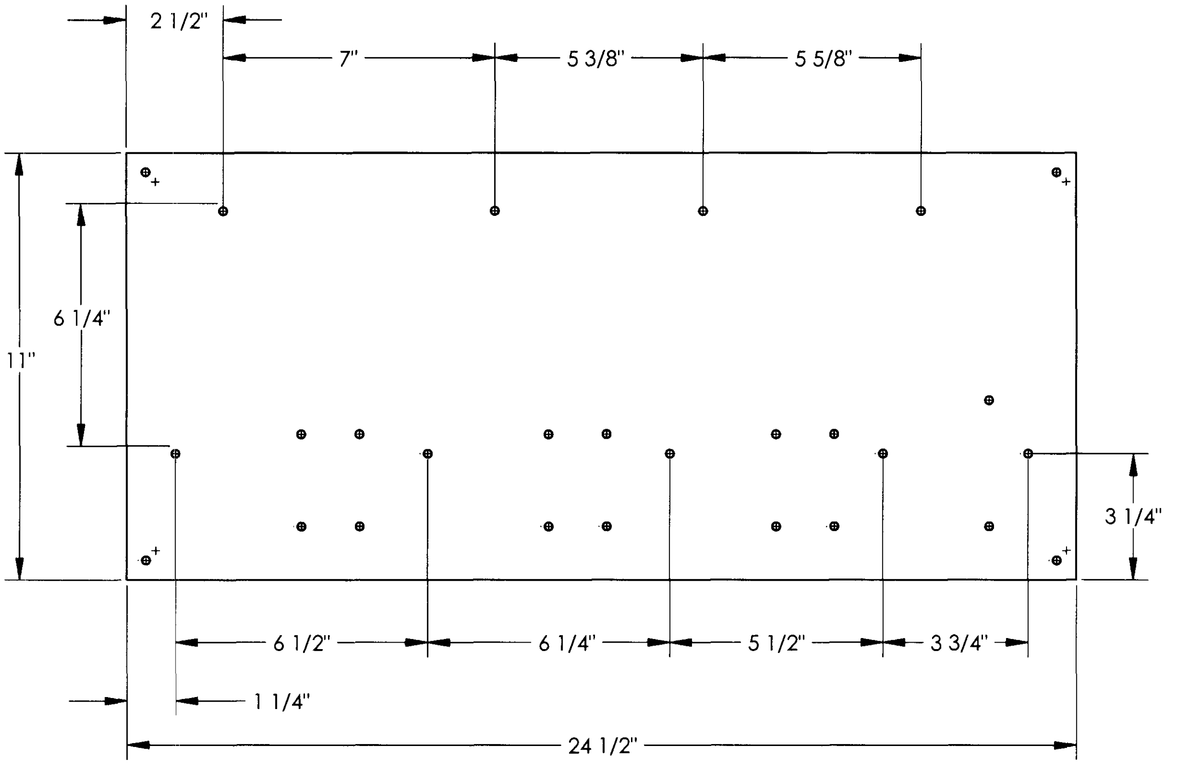

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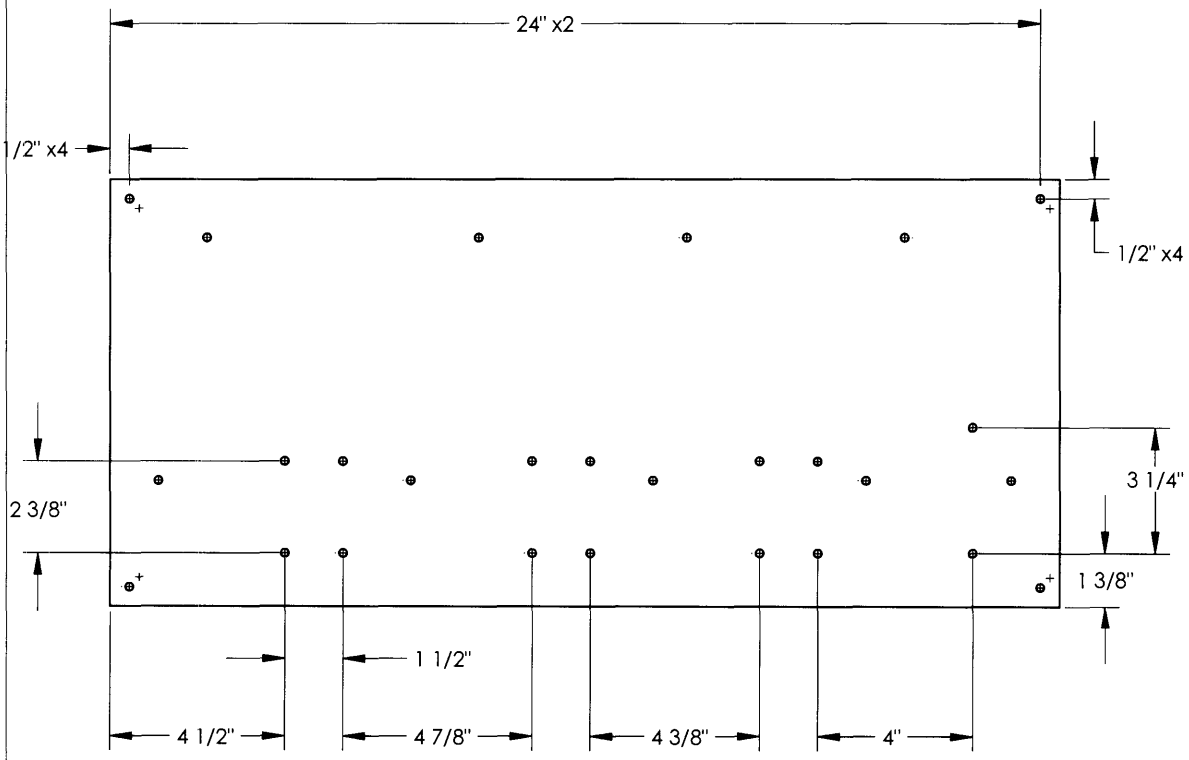

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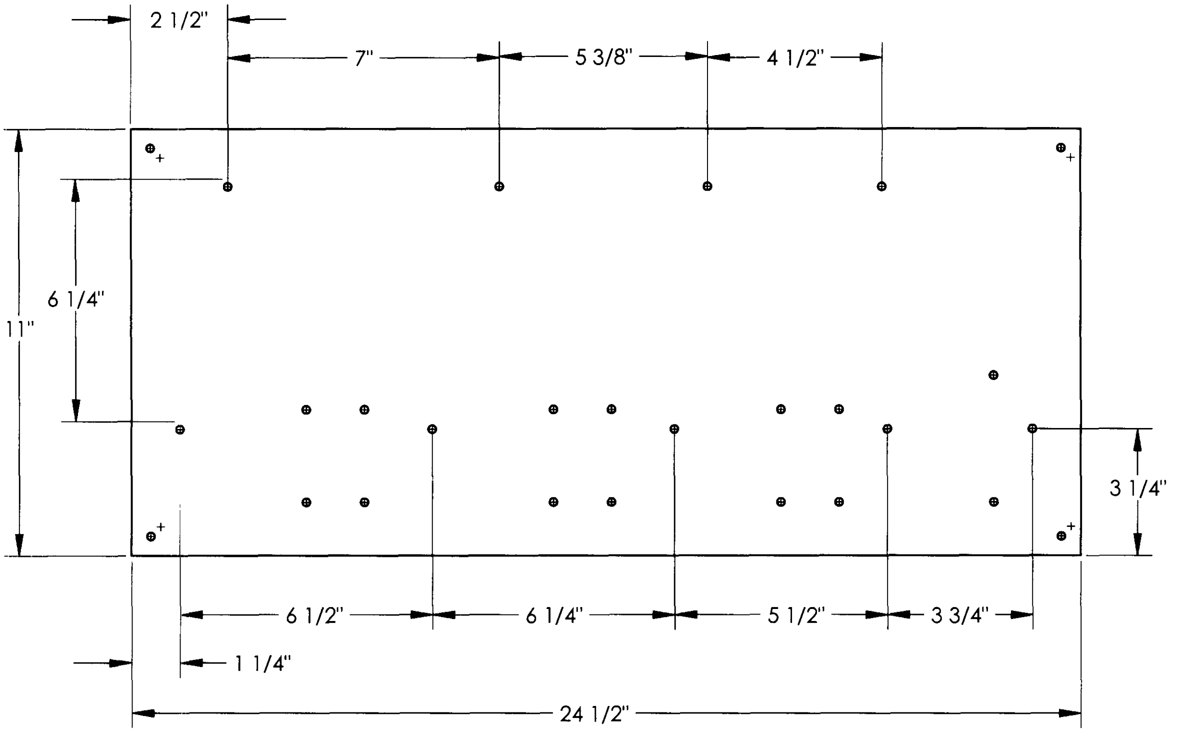

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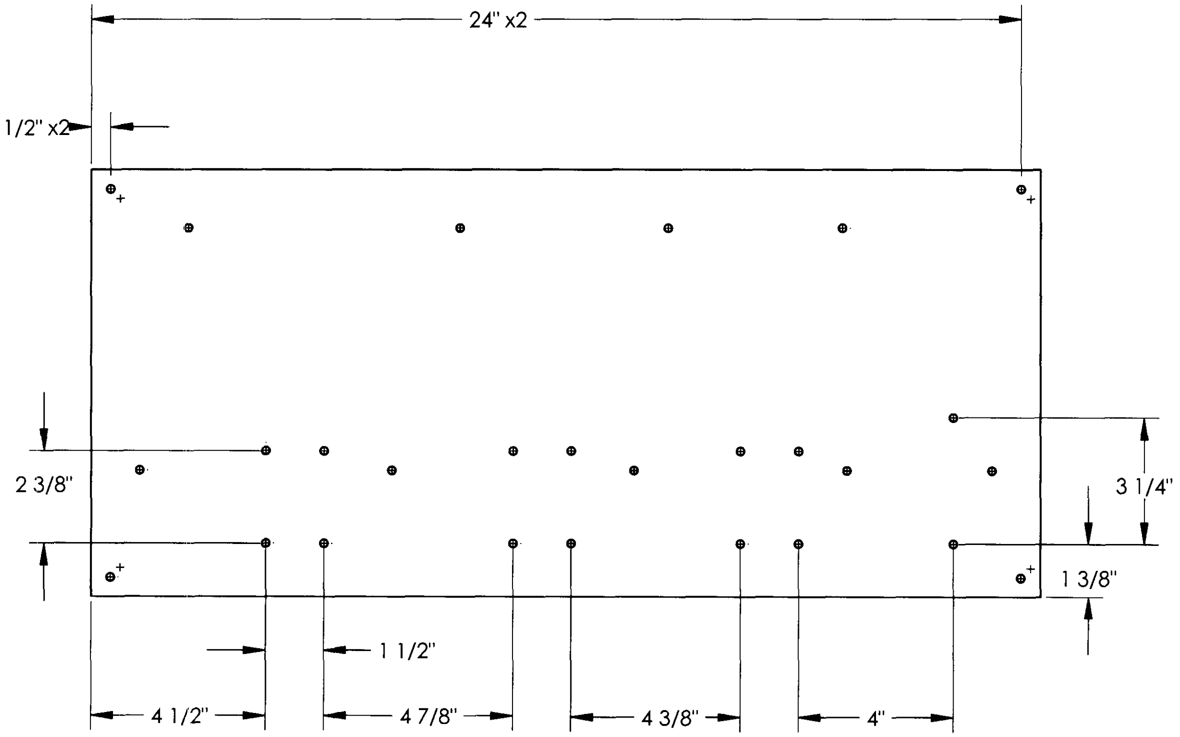

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