iSTEMi Independent Research Project Final Lab Report

Instruments: An Intersection of Engineering and the Arts

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2018-2019

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Purpose:

Music has always been an integral component of my life. At an early age, I played the piano for a few years. Then, in middle school, I picked up the violin and have been playing it exclusively since. I learned that a vital, yet overlooked aspect of being a violinist is that of violin maintenance. This comes with a greater understanding of the functionalities of each of the working parts of a violin. However, for years, I had the luxury of buying new violin parts already premade, and so I never really understood the intricacies of these parts and the difficulties that actual violin luthiers faced when making these parts from scratch. This curiosity of instrument construction also extended to flutes and other categorically variant instruments. Given the task of a year-long, independent engineering project, I decided to take advantage of this opportunity to explore and combine two of my favorite areas of study: engineering and performing arts.

Abstract:

The goal of this project was to build instruments that allow for a physical examination of the various properties of the physics of sound. These instruments were also to be made as close in functionality to their actual counterparts as possible. While comfort and aesthetics were

certainly factors in the construction of these instruments, they were not of as large importance. In order to be able to determine what parts were essential for each instrument, each instrument must be categorized by one or multiple classification systems. Then, adjustments and alterations must be made using engineering approaches to the actual instruments' construction. These alterations were necessary as the Makerspace lacks certain tools and materials employed by professional luthiers, but makes up for these deficiencies with the availability of other equipment, such as 3D printers and laser cutters, that are customary for STEM-related projects but would not be commonly found in a luthier shop. The purpose of this lab report is to first approach the problem of instrument classification and the many classification systems that are commonly used today, then dive in depth into the actual step-by-step process of the construction of each instrument and discuss the various engineering solutions used to tackle the multiple issues faced during construction.

Background:

Western Instrument Classification:

One instrument classification system that is usually well acquainted with most Americans is the Western classification system. In the Western system, instruments are grouped into string, woodwind, brass, and percussion instruments. String instruments are self-explanatory - they include instruments with strings like violins and cellos. Woodwind instruments are air columns that are blown to produce sound, and they include flutes, oboes, and clarinets. Brass instruments are also blown, but are made of brass and consist of valves rather than a single air column - they include trumpets, trombones, and tubas. Finally, percussion instruments produce sound by being struck, either by being struck, shaken, scraped, or otherwise, and they include xylophones, triangles, and many different types of drums. The following figure provides an example of how

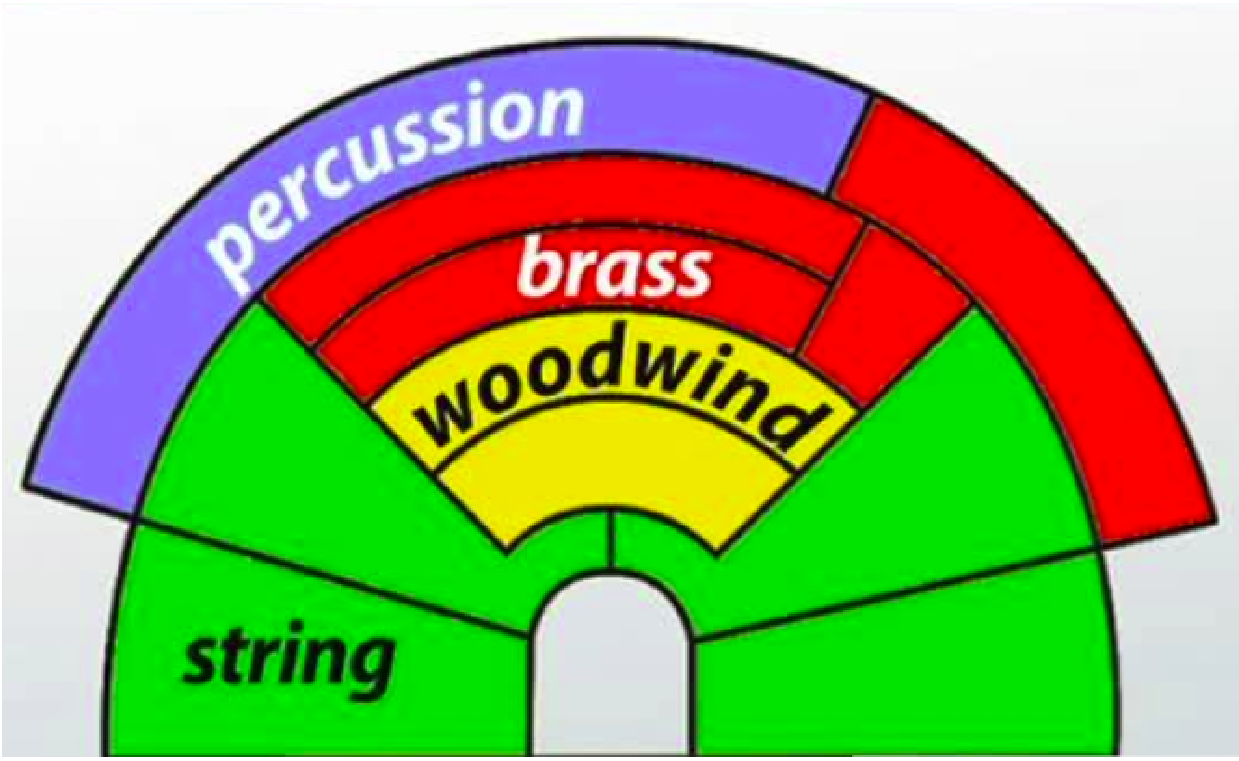

Figure 1: A common Western orchestral set-up. Sections are defined by the placement of the four families of instruments as defined by the Western classification system.

these four instrument families would be commonly grouped in an orchestral setting. In this way, the Western classification system is very useful as it clearly defines the grouping of each of the instruments that would commonly be found in a traditional orchestra by their common traits and modes of sound production.

However, as is inherent in its naming, the Western instrumental classification is almost always used to classify Western instruments, or those that would commonly be found in a Western-style orchestra. This means that the plethora of other instruments, ranging from traditional instruments from third-world cultures to modern instruments that generate sound using electricity, remain unclassified. Some examples of these are the mayuri (*see Figure 2*), a

Figure 2: Mayuri: an instrument with a bowed stringed neck that is played in a kneeling position. The instrument is shaped to look like a peacock and is made with real peacock feathers and bills. It features moveable arched metal frets and a parchment belly. The instrument is traditional to Hindu culture.

stringed instrument with peacock feathers traditional to Hindu culture, and the theremin (*see Figure 3*), an increasingly popular electric instrument.

Figure 3: Theremin: an instrument that generates sound using electricity. Sound is described as a cross between a saxophone and a slide whistle. Players wave their hands near the antennae to raise or lower the theremin's pitch and volume. The antennae connect to a complex system of circuits, oscillators, coils, and wires within the main box of the theremin.

Another issue with the Western instrument classification system arises when trying to classify instruments that use mechanics belonging to multiple Western instrumental families in order to generate sound. An infamous example of this paradox is the piano - when a player hits the piano keys, levers cause a small hammer to hit strings of specific length and tension within the piano. The corresponding vibrations of these strings are what listeners process as sound. The question thus arises: is a piano a percussion instrument because of the percussive action of hammers hitting strings to produce sound, or is a piano a string instrument because it is the vibration of strings that creates sound? By the Western instrumental classification system, which categorizes instruments into string, woodwind, brass, and percussion instruments, instruments like the piano remain ambiguous. Luckily, there is a way to properly categorize each and every instrument, regardless of whether it is a Western orchestral, traditional, or modern electronic instrument. We will explore this method of classification, which takes a closer look at the specifics of sound production, in the following section.

Hornbostel-Sachs Instrument Classification:

While the Western instrument classification system categorizes instruments by their general appearances (having strings, made of brass, etc.), the Hornbostel-Sachs instrument classification system analyzes the qualitative method of how each particular instrument produces sound. In specific, the Hornbostel-Sachs instrument classification system contains four categories: idiophones (produce sound by vibrating themselves), membranophones (produce sound by vibrating a membrane), chordophones (produce sound by vibrating strings), and aerophones (produce sound by vibrating columns of air). Examples of idiophones include xylophones, cymbals, and marimbas. Examples of membranophones include snare drums and bass drums. Examples of chordophones include violins and cellos. Examples of aerophones include flutes and clarinets. A fifth category, electrophones (produce sound using electricity), was a recent addition to the Hornbostel-Sachs system due to the increasing popularity of electrical instruments in recent decades.

The main advantage of the Hornbostel-Sachs instrument classification system over the Western instrument classification system is that by grouping instruments solely on their physical method of sound production, every single instrument is able to be categorized, not just Western or orchestral instruments. For example, the Hindi mayuri mentioned earlier featured both bowed strings (typical of string instruments) and a parchment belly (typical of percussion instruments), leaving it unable to be classified by the Western classification system. Using the Hornbostel-Sachs classification system, it is evident that the mayuri is a chordophone, as the origin of sound production is through the vibration of strings by the use of a bow, whereas the parchment belly mainly serves to amplify the resonance created by the string. Considering the second earlier-mentioned example of the theremin, which being an electric instrument was unable to be classified through the Western classification system, this instrument falls neatly into the electrophone category of the Hornbostel-Sachs classification system.

Being able to properly classify instruments through either the Western or Hornbostel-Sachs instrument classification systems is essential for understanding the basis of how each instrument is able to produce sound. Upon understanding modes of sound production, one is able to determine the significance in function of each part of the instrument. Knowing the role played by each part on an instrument enabled me to make decisions on materials, construction processes, and aesthetics when engineering the design of each instrument. Having thoroughly discussed instrumental classification, this report will now conduct an in depth examination of the construction and physics of the three instruments I built throughout the year: the violin, the tubulum, and the pan flute.

Violin:

What is it?

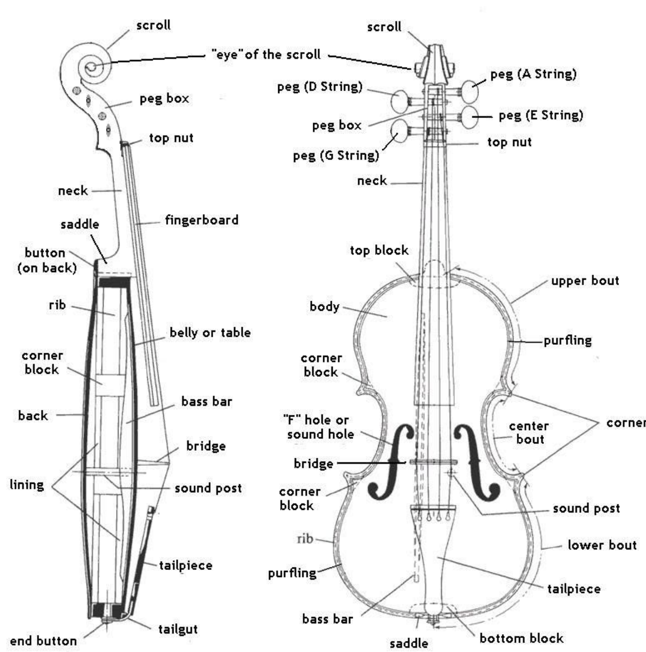

Figure 4: A diagram of the many parts of a standard, classical violin.

A violin is a chordophone featuring four strings that are bowed. The essential parts for producing sound on a violin (*see Figure 4*) include but are not limited to: 1) Peg box and four pegs - a string is wound through and around each of these four pegs and twisting the pegs adjusts the tension of the string, therefore changing its frequency and pitch. The pegs are held in place by friction against the peg box. 2) Four strings - each string plays a different note, increasing in frequency from left to right (G3, D4, A4, E5). Placing a finger along different locations on the string decreases its effective wavelength, producing a note of higher frequency. 3) Violin body - the main structural component of the violin, usually made of wood. It is connected along its length by ribs and features two f-holes that allow sound to escape from within the body. The two faces of the body are connected by a wooden sound post located inside the violin that is held up by friction.

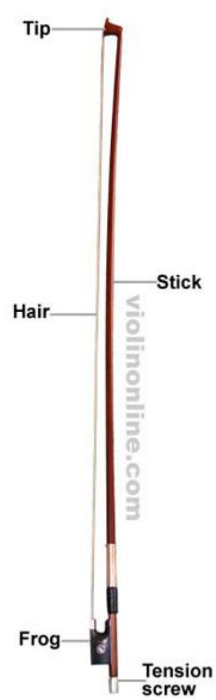

Figure 5: A diagram of the many parts of a standard, classical violin bow.

A bow (*see Figure 5*) is drawn across the four strings to produce sound. The hair on a violin bow is usually made of horsehair, although it can be produced synthetically as well. The horsehair is tightened by an internal screwing mechanism, then covered in rosin made from tree sap to increase the friction of the hair. This allows the hairs to catch on the strings, producing a louder, clearer, more sustained tone.

How it works:

In order to understand how a violin, or rather any instrument, works, one must first understand the concept of resonance. Resonance is defined as “the reinforcement or prolongation of sound by reflection from a surface or by the synchronous vibration of a neighboring object”. Essentially, the vibrations of one object will cause nearby objects to vibrate at a corresponding frequency, leading to air waves likewise oscillating at a specific frequency. These air waves, or sound waves, travel to and are picked up by muscles and nerves in the ear, which then are processed and interpreted by the brain as different sounds.

When a bow is drawn across a string, the friction between the two objects causes the string to vibrate longitudinally. The frequency of this vibration is determined by the wavelength of the string. When no fingers are placed on the string, the effective wavelength is the distance between the top nut and the bridge of the violin, or the two main contact points that the string has with the body of the violin. When a finger is placed along the string, the effective wavelength is shortened to the distance between the finger and the bridge, producing a higher-pitched sound. These vibrations cause the wooden bridge to vibrate, which in turn causes the top face of the body to vibrate. Vibrations travel down the sound post, causing the bottom face of the body to vibrate. This now rapidly vibrating body of the violin causes the air waves within the violin to oscillate, and the air escapes through the f-holes of the violin. This is the sound that one hears when playing a violin.

Construction:

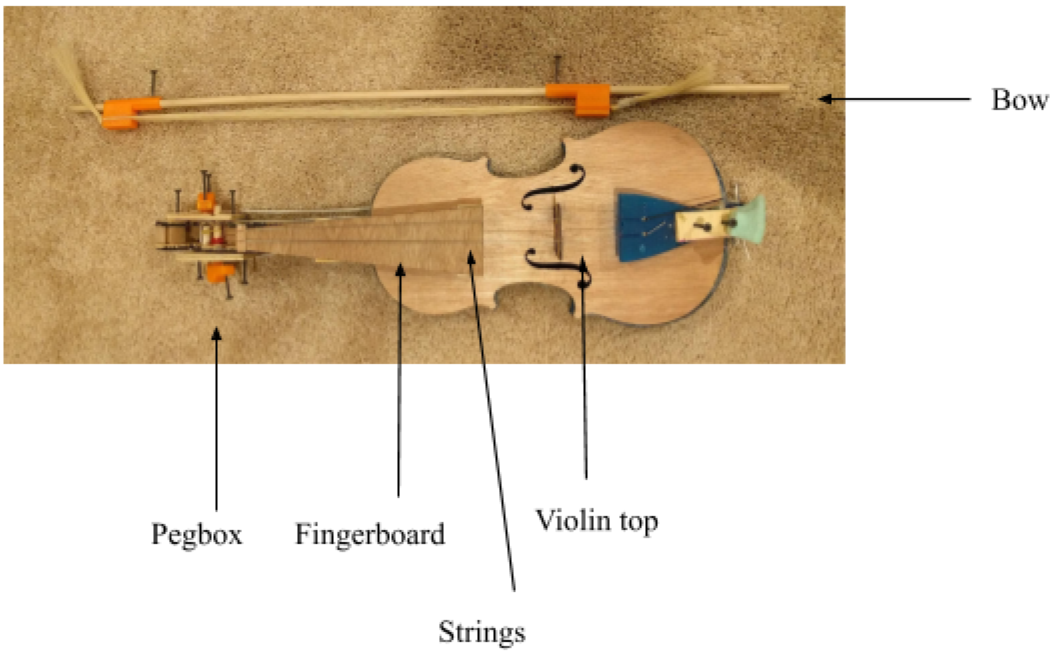

Figure 6: A diagram of the final product of the first iteration of the violin and bow.

The main theme that occurred when constructing the violin (*see Figure 6*) was making adjustments wherever possible without compromising the integrity and functionality of the violin. Although we did not have the exact maple planks that would normally be used for violin wood, we knew that the parts essential for resonance still needed to be made of wood rather than plastic or some other material, as wood is flexible and can transmit vibrations. Luan plywood was used as a substitute for maple because it was sold in thin, ⅛" boards and was relatively flexible and cheap. For both faces of the body of the violin, I used the laser cutter to precisely cut the outline of the body and f-holes out of thin boards of luan. The intricate bridge and bass bar were also laser cut out of the same luan. The fingerboard was also laser cut using luan. ¼" wooden dowels were used for the sound post, pegs, and bow stick. Medium-density fibreboard was cut using the CNC machine to generate the shape of the neck and scroll. The orange pieces used for the frog and tip of the bow as well as the pegs were printed out of PLA using the 3D printer. Finally, the tailpiece and ribs were printed out of resin using the resin printer. I was unable to make my own metal violin strings or horsehair for the bow, so I bought a set of full-size Prelude edition violin strings as well as one set of imported synthetic horsehair. Normally, the entirety of the violin, excluding the strings and bow hair, would be made out of wood. However, I was only able to cut flat shapes out of the luan, as I did not have a heating iron that professional violin luthiers would use to heat up, bend, and shape wood into the desired shape. Therefore, I was able to substitute 3D-printed and resin printed parts for the parts on the violin that weren't necessary for resonance.

Because I was using simplified shapes and materials in the construction of the violin, I had to make some simplifications and adjustments to the many intricate mechanisms that would be found on a standard, classical violin. For example, the pegs are normally tapered, so that they may be held in place by friction when pushed in the peg box, or loosened to be able to be turned for tuning when pulled out of the peg box. Since I was just using a non-tapered wooden dowel, I had to use screws to hold the pegs in place. Although they did prevent the pegs from slipping when tension was applied to the strings, they were not a perfect substitute, as the screws were not flush with the MDF scroll, allowing for some small variation in pitch from the desired frequency when tuning. Additionally, the strings normally attach to fine tuners located on the tailpiece of the violin, a very complex mechanism that allows the player to twist a gear-mechanism for very minute tuning adjustments. Since I had no idea how to make this gear mechanism, or how to implement it into the already difficult design for the resin-printed tailpiece, I simply took allen wrenches, inserted them into the tailpiece, and stuck the ends of the strings onto the allen wrenches. I then positioned the wrenches in such a way that the strings would not slip off of the wrenches when tightened in the tuning process. Screws also had to be used to hold the tailpiece in place, as the resin used to make the tailpiece was relatively brittle and fragile and would fracture or snap completely when tension was applied on it by the strings. Finally, the screwing mechanism that is used on a bow to tighten or loosen the bow hair is the most complex mechanism of the entire violin. It normally begins with a screw at the base end of the bow that attaches to a set of mechanisms located within the frog of the bow that runs through the stick of the bow and connects to a similar mechanism located in the tip of the bow. Recreating this on a cheap, wooden dowel would be nearly impossible, so rather than opting for this complex screwing mechanism, I simply printed two identical frogs using the 3D printer, friction fit the bow hairs within an opening in the frog, then tied knots at each end of the horsehair to prevent it from falling out of the frogs when pulled. The makeshift PLA frogs would then be held in place at end end by screwing it through the dowel.

Contact cement and superglue were used to bind the wooden parts of the body with the resin printed ribs and tailpiece. Hot glue was then applied along the seams, not for its adhesive properties, but so that it would fill in any potential gaps or cracks along the body of the violin that would prevent the violin from producing a loud, clear tone. Finally, a large problem with the violin was that the body and the neck and scroll of the violin would bend under the large force of the tension of the strings. To counteract this, silicone sealant was placed along the neck and body. Wires were also tied loosely around the back of the violin along the scroll and tailpiece in such a manner so that they would tighten as a balance of tension against the strings.

Data:

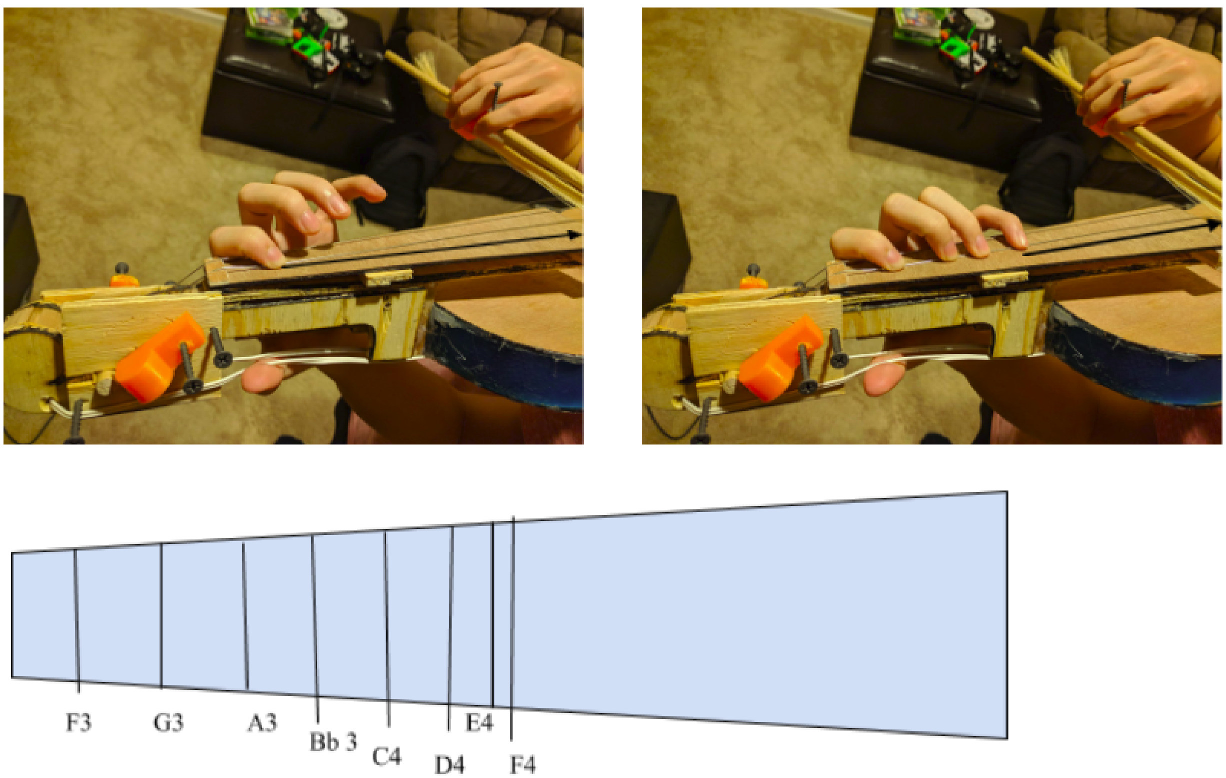

Figure 7: Diagrams showing how the violin changes when generating different pitches

The above diagrams (*see Figure 7*) show how the effective string length (shown as an arrow from the closest finger touching the string) is the primary factor in determining the pitch that is played by the violin. The wave frequency increases as the effective string length is shortened by placing more fingers down onto the string. Twisting the pegs or placing fingers far apart from each other can result in distinctly different notes being produced, while more minute adjustments of the finger can result in finer tuning of a note.

Additionally, the following data tables (*see Figure 8*) show the relation between effective string length (defined as the distance between the end of the string fastened on the tailpiece and the position of the finger along the string) and pitch for five possible notes that are able to be played on one string of the violin.

Relation between Effective String Length and Pitch for 5 Notes

**Effective string length is measured as the distance between the end of the string fastened on the tailpiece and the position of the finger along the string.*

G3

Effective String Length (cm)	Frequency Generated (Hz)
39.1	195.8
39.0	197.3
38.9	200.3
38.8	204.5
38.7	207.4

A3

Effective String Length (cm)	Frequency Generated (Hz)
35.2	218.2
35.1	220.3
35.0	224.1
34.9	228.6
34.8	232.5

B3

Effective String Length (cm)	Frequency Generated (Hz)
32.1	240.1
32.0	243.3
31.9	246.9
31.8	250.2
31.7	252.3

C4

Effective String Length (cm)	Frequency Generated (Hz)
30.5	253.2
30.4	256.1
30.3	258.5
30.3	259.5
30.2	261.6

D4

Effective String Length (cm)	Frequency Generated (Hz)
27.1	286.9
27.0	289.1
26.9	291.3
26.8	294.5
26.7	296.7

Figure 8: Relation between Effective String Length and Pitch for 5 Notes. Effective string length is measured as the distance between the end of the string fastened on the tailpiece and the position of the finger along the string.

Tubulum:

What is it?

Figure 9: A box containing all 8 tubes for a G-major scale from G3 to G4. A rubber paddle serves as a mallet for striking the elbow joint on one end of each pipe to generate a note.

The tubulum (*see Figure 9*) is an example of aerophone, meaning it produces sound through the vibration of a column of air. Before we discuss the tubulum specifically, however, it is important that one knows the two main types of aerophones, open and closed, and understands the similarities and differences between the two.

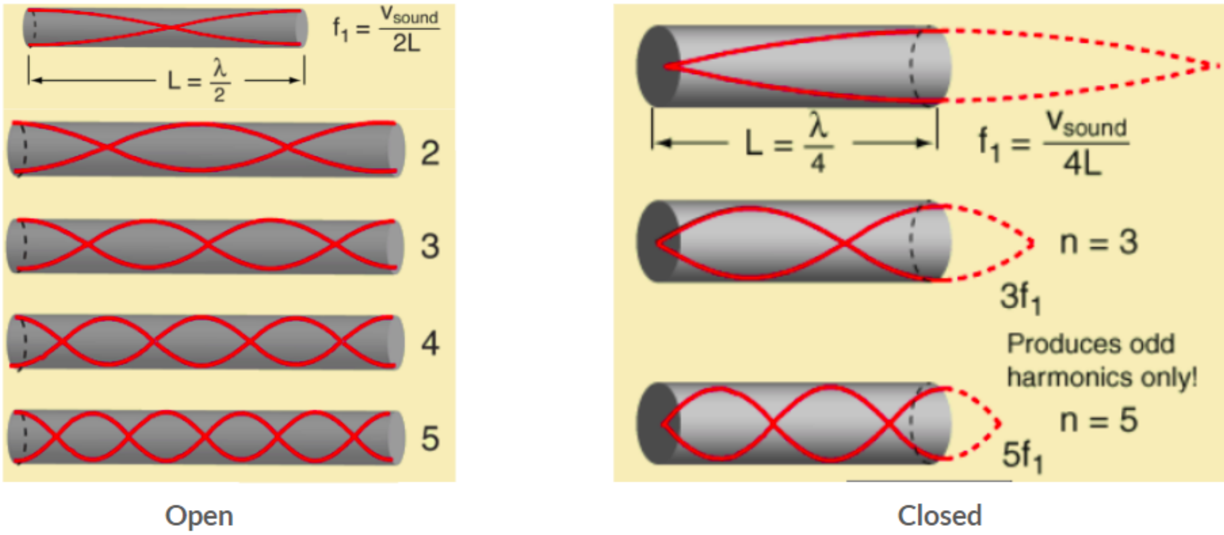

Figure 10: Diagrams of the fundamental frequency and harmonics of open air columns (left) and closed air columns (right). The equations shown represent the relation between the frequency f of the wave, the velocity v of the wave, and the length L of the air column.

Open air columns are air columns that are open on both ends (ex. flute). Closed air columns have one end of the air column closed (ex. clarinet). There are also closed air columns that are closed on both ends, but these are rarely used in music so this report is not going to discuss them.

When you excite the air in an open column, it produces a sound wave with a wavelength of twice the length of the column (*see Figure 10*). Because the column is open, the wave has antinodes at both ends of the column. The pressure that is generated of the air in the column quickly drops to atmospheric pressure upon leaving the column. Generally, the speed of a wave equals the frequency of the wave times the wavelength. Since you know the length of the wave is 2 times the length of the column, you can substitute 2L for wavelength and rearrange the equation to solve for frequency. This lowest possible frequency that you can get on an open air column is called the fundamental frequency. You can also produce harmonics, which are just multiples of the fundamental frequency. For example, the 2nd harmonic is 2 times the fundamental frequency, 3rd is 3 times, and so on.

When you excite the air in a closed column, it produces a sound wave with a wavelength 4 times the length of the column (*see Figure 10*). This is because since the column is closed at one end, you get an antinode at the open end but a node at the closed end. When the wave reaches the closed end, it bounces off of the end without losing any pressure. This is due to Newton's 3rd law, which states that every action, there is an equal and opposite reaction. Only when the wave reaches the open end again does the pressure of the wave drop to atmospheric pressure. Since the wavelength in a closed column is 4 times the length of the column, the equation for solving for the frequency of the wave uses 4L instead of 2L as is the case in open air columns. One thing to note about closed air columns is that since it has that closed end which causes the wave to reach a node, one can never obtain even harmonics of the fundamental frequency, only odd harmonics.

How it works:

Back to the specific example of the tubulum, the tubulum is an example of an aerophone with an open air column. The end of a pipe is struck with a rubber paddle, causing the column of air within the pipe to vibrate and be released out of the other end. This vibrating air then reaches our ear and is interpreted by our brains as sound.

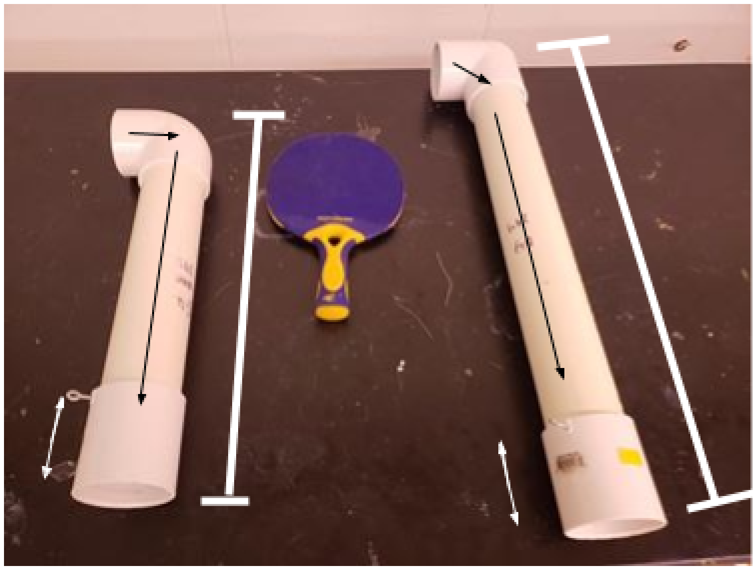

Figure 11: A labeled diagram showing how the notes on a tubulum differ to produce variant pitches. The shorter tube (left) produces a higher frequency note while the longer tube (right) produces a lower frequency note.

The length of each tube primarily determines the pitch (full white length, *see Figure 11*). The air moves from the elbow joint at the top of the image down (black arrows) out the ending. For fine tuning, the position of the coupling on the end of the tube is adjusted (double headed white arrow).

Construction:

Each key of the tubulum consists of a 2'' PVC pipe with a PVC elbow on one end that is struck with a rubber paddle, and a PVC coupling on the other end. The PVC pipes were first measured, then cut with a PVC cutter. The notch located on the inside of the PVC coupling was sanded away using a dremel to allow for full movement. The coupling was then fastened to the pipe with an I hook. The length of the tube is adjusted by a movement of the PVC coupling on one end of the pipe, and this change in tube length corresponds with a change in the wavelength and frequency of the sound waves that are generated by a strike of the paddle and thus a change in pitch. When the coupling is adjusted farther off of the tube, the overall tube length increases, the sound frequency decreases, and the pitch lowers. When the coupling is adjusted closer on to the tube, the overall length decreases, the sound frequency increases, and the pitch rises. Whereas the different lengths of each of the eight pipes result in the generation of eight distinct notes, adjustments of the couplings on each of these pipes allows for more minute changes in pitch.

Data:

Changes in note frequency and pitch are caused by either an increase or decrease in the size of the PVC pipe, or an adjustment outwards or inwards of the PVC coupling. Increasing the size of the pipe or adjusting the coupling outwards both increase the effective wavelength of the air waves generated when the column is struck with the rubber paddle, causing the frequency and pitch of the note played to decrease. Decreasing the size of the pipe or adjusting the coupling inwards both decrease the effective wavelength of the air waves generated when the column is struck with the rubber paddle, causing the frequency and pitch of the note played to increase.

The following data tables (*see Figure 12*) show the relation between key (pipe) length and pitch for five possible notes that are able to be played on the tubulum.

Relation between Key Length and Pitch for 5 Keys

G3

Length of Key (cm)	**Frequency Generated (Hz)**
85	195.8

86	197.3
87	200.3
88	204.5
89	207.4

A3

Length of Key (cm)	Frequency Generated (Hz)
74	232.5
75	228.6
76	224.1
77	220.3
78	218.2

B3

Length of Key (cm)	Frequency Generated (Hz)
67	240.1
68	243.3
69	246.9
70	250.2
71	252.3

C4

Length of Key (cm)	Frequency Generated (Hz)
64	253.2
65	256.1
66	258.5
67	259.5

68	261.6

D4

Length of Key (cm)	**Frequency Generated (Hz)**
56	296.7
57	294.5
58	291.3
59	289.1
60	286.9

Figure 12: Relation between Key Length and Pitch for 5 Notes.

Pan Flute:

What is it?

Figure 13: A pan flute constructed out of 8 polyethylene terephthalate bottles and a plywood board stand. Note frequency is adjusted by increasing or decreasing the amount of water filled within each bottle.

The pan flute is an example of an aerophone with one closed end, meaning it produces sound through the vibration of air. 8 different keys, which are in this case bottles, play the 8 different notes of a G-major scale from G3 to G4. Blowing across the top of an opened bottle acts as the propagator of the resonance of air within the bottle. The stand allows the player to play all 8 bottles in a standing position so that a series of notes may be produced by simply moving left and right. The bottles are held in the stand merely by friction, allowing the player to also have the option of removing bottles individually to play single notes.

How it works:

As previously mentioned, the pan flute is a closed end air column, with the closed end of the bottle being the literal closed end, while the unscrewed mouthpiece of the bottle represents the open end. Blowing a continuous, steady, flat stream of air causes resonance to occur within the bottle. However, due to the shape of the bottle being more of a cavity than cylindrical column, a special type of resonance occurs within the bottle called Helmholtz (cavity) resonance, which has to do with changes in air pressure that occur when a player blows into a cavity. More specifically, blowing into a bottle increases the air pressure within the bottle, and air waves within the bottle oscillate at a frequency determined by the shape of the bottle. The high air pressure inside the bottle causes more air to be forced out of the bottle than was originally blown into the bottle. This release of air travels to our ears as waves and is interpreted by our brains as signals and impulses of sound. The reason why the player must blow across the top of the bottle as opposed to directly into the bottle is because the player must blow at an angle that allows air to be released from the bottle. Otherwise, Helmholtz resonance will not occur. In this case, the wavelength of the air waves is equal to the length of the cavity, or the bottle. Filling the bottle with water decreases the volume of air within the cavity, decreasing the wavelength and increasing the frequency of the note that is produced. Thus, adding water raises the pitch of the note, and removing water lowers the pitch of the note. In addition to the amount of water within the bottle, the actual shape of the bottle plays a role in Helmholtz resonance as well. Increasing the size and volume of the bottle lowers the frequency of the note produced. Increasing the diameter of the neck of the bottle increases the frequency of the note produced. Additionally, increasing the length of the neck of the bottle decreases the frequency of the note produced.

Construction:

A traditional pan flute consists of 8 pipes, ranging in material from wood to metal, that are open air columns, as a traditional flute is. Differing lengths of the 8 pipes produce 8 different notes when the pipes are blown across, with a longer pipe translating to a lower note and a shorter pipe translating to a higher note (*see Figure 10*). However, I decided that this concept was too similar to the tubulum, and wanted to illustrate the characteristics of both open and closed air column aerophones. Thus, instead of using 8 open pipes of different lengths, I used 8 closed water bottles of the same length, the independent variable in question being the amount of water added to each bottle rather than the length of the bottle.

Figure 14: A modified pan flute, using 8 identically-sized bottles filled with water at different levels to represent the 8 different notes of a scale. The lowest note, G3 (leftmost bottle), has no water inside the bottle. The highest note, G4 (rightmost bottle), has the most water inside the bottle of the 8 bottles.

To build this modified pan flute (*see Figure 14*), I obtained 8 commercially-produced polyethylene terephthalate bottles and filled them with varying amounts of water to obtain the 8 notes of a G-major scale from G3 to G4. I then built a plywood stand with 8 circular openings along the top with a diameter equal to the diameter of the indented portion of the middle of each bottle, so that the bottles would be able to rest within the stand using just friction without any sort of adhesive to allow for easy removal and insertion of the bottles into the stand.

Data:

Changes in frequency and pitch are generated by filling or removing water from each bottle. Adding water increases the frequency and pitch of the note produced, while removing water decreases the frequency and pitch of the note produced. While characteristics of the shape of the bottle are also factors in determining the frequency and pitch of the note produced, these variables were controlled so that the only variable changing between each of the 8 bottles was the amount of water within each bottle.

The following data tables (*see Figure 15*) show the relation between the amount of water in the bottle and pitch for five possible notes that are able to be played on the pan flute.

Relation between Amount of Water in Bottle and Pitch for 5 Keys

G3

Amount of Water (oz)	Frequency Generated (Hz)
0	195.8
0.3	197.3
0.6	200.3
0.9	204.5
1.2	207.4

A3

Amount of Water (oz)	Frequency Generated (Hz)
2	232.5
2.3	228.6
2.6	224.1
2.9	220.3
3.2	218.2

B3

Amount of Water (oz)	Frequency Generated (Hz)
4	240.1
4.3	243.3
4.6	246.9

4.8	250.2
5.2	252.3

C4

Amount of Water (oz)	Frequency Generated (Hz)
6	253.2
6.3	256.1
6.6	258.5
6.9	259.5
7.2	261.6

D4

Amount of Water (oz)	Frequency Generated (Hz)
8	296.7
8.3	294.5
8.6	291.3
8.9	289.1
9.2	286.9

Figure 15: Relation between Amount of Water and Pitch for 5 Notes.

Conclusion:

The goal of this project was for me to explore the intersection of engineering and the arts by designing and building my own instruments that would allow me to closely examine the many different yet interrelated properties of the physics of sound. While my original plan consisted of just replicating a violin, an instrument that has special and important meaning to me, my expanse of knowledge of the physics of sound and music has far exceeded my initial expectations. This report covers: two types of instrumental classification systems and their defining characteristics, the construction of a chordophone (violin), the construction of two aerophones, one being an open air column (tubulum) and the other a closed air column (pan flute), and the properties of resonance on a fixed string, an open air column, a closed air column, and a cavity. I was also able to test out each instrument and gather data through controlled experiments involving the relation between the change of one variable and the change in frequency of the note produced. I hope that this research will invite readers to relate to ideas of the physics involved when listening to different genres of music produced on different types of instruments, as well as make connections to the arts when learning about famous physics examples in a physics-based setting, like spring properties, simple harmonic motion, and more.

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