The Ancient Hydraulis, a Reconstruction

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Introduction to the Hydraulis

Physical Description

A hydraulis, known colloquially as a water organ, was chosen for this project. The hydraulis is an instrument that uses the flow of air through pipes of different lengths to cause sounds of varying pitches (Vitruvius, *On Architecture*, 10.8). This is done through hand pumps attached to the side of the instrument which must be constantly pumped while the instrument is being played. Additionally, to keep the airflow through the pipes consistent, the cistern into which the air is pumped is partially filled with water. This means that despite the inconsistent rate of air flowing into the instrument, the air pressure inside does not change, allowing the output of air to be at a constant rate. To facilitate this, the cistern tended to be from 60 to 90 centimeters tall, and the overall height of the instrument, including the base, air chamber, and pipes themselves was typically 165 to 185 centimeters tall (McKinnon, 2001, p. 2).

Archaeological records of the hydraulis are rare and typically only exist as fragments. There are, however, several pictorial representations of the instrument across many mediums including mosaics, carvings on coins, and even clay models. These depictions, along with literary accounts of the hydraulis, enable historians to be relatively confident in reconstructions, despite the lack of any fully preserved instances of the instrument (Apel, 1948, p. 192).

General History

The hydraulis was invented around 300 BCE by an Alexandrian engineer named Ctesibius. Ctesibius was a practical thinker and developed several innovative technologies over his life, including a number of inventions that made use of hydraulics and pneumatics (Mckinnon, 2001, p. 1). None of Ctesibius' writing remains, but other ancient writers such as Vitruvius discuss his inventions, including the hydraulis (*On Architecture*, 10.8.4-10.8.5).

Unlike many complex technologies, the hydraulis was not pieced together over a long period of time or developed by multiple individuals. Instead, the record shows that Ctesibius developed all of the necessary parts to build the instrument, as almost none of the parts have any written record before their description as part of the hydraulis (Perrot, 1971, p. v).

Eventually, the hydraulis was replaced by the pneumatic organ, with the last authentic reference to the hydraulis being by Sidonius Apollinaris around 450 CE when he mentioned their decreasing popularity (Apel, 1948, p. 199) (*Letters of Sidonius*, 1.2.6).

The pneumatic organ was very similar to the hydraulis, except the hydraulic aspects of the instrument were replaced by bellows as the method of maintaining the constant air pressure in the instrument (Apel, 1948, p. 199). Because of this change, the pneumatic organ offered several improvements, namely being lighter, less susceptible to corrosion, and cheaper than the hydraulic alternative, all of which led to the eventual replacement of the hydraulis. The two instruments did exist simultaneously for centuries, as the physical remains from a pneumatic organ date back to at least 228 CE (McKinnon, 2001, p. 6).

Use of the Hydraulis

Purpose

The hydraulis was likely not received or viewed as a musical instrument immediately after its invention. Instead, since the hydraulis combined several new technological elements, including advancements in hydraulics and pneumatics, the invention was considered to be a mechanical and technological showcase when it was first constructed (Mckinnon 2001, p. 1). By 90 BCE, evidence of a successful hydraulis player named Antipatros, in the form of an inscription discovered at Delphi, showed the evolution of the device’s purpose from solely a demonstration of technology to a proper musical instrument (Morgan, 2022, p. 289) (Perrot, 1971, p. 44). In fact, the inscription shows Antipatros winning an intensely cutthroat music competition, further illustrating how well respected and musically valued the device became soon after its invention (*Sylloge Inscriptionum Graecarum*, vol. 2 syll. 737). After this, the hydraulis is depicted and discussed as being used as an instrument in a variety of contexts, ranging from large public spectacles in theaters or the circus to smaller private events in domestic settings (Apel, 1948, pp. 196-197) (Morgan, 2022, pp. 290-291). This is partially demonstrated by the writings of Athenaeus, a native of the ancient Greek city of Naucratis, who wrote about the prevalence of the hydraulis as a domestic instrument, showing the private side of the instrument. In contrast, the more public side of the instrument is demonstrated through an anonymous poem dating to around 65 CE in which the hydraulis is mentioned as being used in large theatres (*Aetna*, p. 387) (*Deipnosophists*, 4.75).

The diversity in the instrument's use is further demonstrated through the manner in which it was used by Emperor Nero. It is heavily attested that Nero was a music enthusiast who specifically enjoyed and played the hydraulis (Morgan, 2022, pp. 287-288). In fact, the ancient Roman author Suetonius mentioned Nero's fixation on the instrument in his overview of Nero's life, showing the importance of the hydraulis to the emperor (*The Life of Nero*, 41.2). Nero not only enjoyed the instrument recreationally, but also attempted to use its varied perceptions by the different Roman classes to bolster his public opinion. First, Nero attempted to associate himself with the instrument to gain favor with the general public, who favored the hydraulis mostly due to its connections to public spectacles. Next, Nero tapped into the elevated status of the hydraulis as a technological feat and pleasant instrument for private occasions to appeal to Roman elites (Morgan, 2022, pp. 285, 296).

What this shows is that the hydraulis had a varied set of uses and users. Players ranged from the unnamed individuals shown in depictions of the instrument to emperors, and uses of the technology ranged from being used as one of many instruments at large public events to being used as a political tool and a complex example of pneumatic and hydraulic engineering.

Playing the Instrument

The type of music played on the hydraulis, and the techniques used to play it, are largely unknown, but there are small amounts of textual sources that tangentially and briefly give insight into these topics. The descriptions of the instrument's use generally included some mention of agility and the ability to play the instrument quickly, contributing to the idea that the music being played was similarly quick and that the player was able to use both hands to play many notes at once (Apel, 1948, p. 207). For example, the ancient author Claudian describes the hydraulis as being able to produce "a thousand diverse notes" from the "light touch" of the player's "wandering fingers" (*On the Consulship of Manlius*, 315). This contrasts with the music of the subsequent types of organs, as the method of playing notes on those devices involved pulling slides with the entire hand. This made it impossible to play many notes at once in the same way as when playing on the hydraulis. (Apel, 1948, p. 8). Beyond these limited textual and physical analyses, the music played on the hydraulis, and how it was learned is largely unknown (McKinnon, 2001, pp. 5-6).

Construction of the Hydraulis

Sponsors

There are limited records of the hydraulis in the immediate time following its invention. It is clear that Ctesibius built the first one, and that he did so without a sponsor, as he invented it by himself. The manner in which the device spread and became popular over the next couple hundred years is largely undocumented, meaning the patrons and construction history of the technology during this period are essentially unknown. The only records of the hydraulis around this time are a few scattered mentions of the instrument that occurred before the discussion of Antipatros, in which the hydraulis is depicted as highly popular (Perrot, 1971, pp. 43-44) (*Sylloge Inscriptionum Graecarum*, vol. 2 syll. 737).

Over the following centuries, written records of the hydraulis quickly grew in numbers, forming a clearer picture of the instrument's history. Around this time, the hydraulis was found primarily in the houses of the wealthy, meaning that many of the instruments were likely financed privately by elite members of Roman society. The hydraulis was also popular in more public settings, such as in theatres and arenas. Their use in public suggests that some of the instruments were more publicly funded (McKinnon 2001, p. 6).

Builders

Although the hydraulis was a popular instrument among the people of Rome, its function was largely mysterious to the general public, as the instrument involved several instances of new and innovative technology. Because of this widespread lack of understanding, the hydraulis must have been made by highly skilled and educated individuals who not only had the general technical knowledge to construct a complex instrument, but also had access to the descriptions and explanations of the new technologies that constituted the hydraulis. This means that the number of people who were able to, and did, construct the instrument was small and mostly included builders and inventors (Perrot, 1971, pp. 43-44). Some members of the elite class, such as Nero, also took an interest in the hydraulis. Although they likely did not construct the instruments themselves due to social and cultural norms and a general lack of engineering and construction experience, they were also highly knowledgeable about the design and inner workings of the instrument (Morgan, 2022, p. 300).

<u>Focused Discussion</u>

Reason for Project Choice

Both Geoffrey and Annie became very invested in pursuing a hydraulis for the final project early in the semester, after learning about it in class and through the readings. Proximity in classroom seating led to the hydraulis being discussed as a potential project with Nate, Julia, and Taylor who were intrigued by the idea of constructing a working musical instrument. Overall, this project was decided on because many members of the group have experience playing an organ, piano, or other musical instrument and the personal connection to music made this project compelling. Additionally, the group felt that a more challenging, technical project with many moving parts and complex details would be very rewarding.

Planning of Scale, Approach, Materials, & Labor

The main goal when designing the project was to make a playable organ. To achieve this, the organ would need to be large enough to produce the volume of pressurized air required to play different notes through the pipes and could not be built on a smaller scale. Ancient sources lack information on the exact dimensions of the hydraulis. Consequently, the dimensioning for this project was based on a combination of analysis of ancient depictions of the hydraulis, modern schematics that better detailed the interior components, and the dimensions of available materials. Once a five-gallon bucket was chosen for the water chamber, the dimensions of the organ were selected so that ratios from antiquity could be maintained. For example, in ancient artistic renderings, the ratio of the diameters of the inner and outer chamber appeared to be around 2:3. The bucket measured 12 inches wide, so a total width of 18 inches was selected for the main chamber. Similarly, the ratio of the height of the inner and outer chambers was approximately 1:2 and the main octagonal altar was designed to be 27 inches tall, which is approximately twice the height bucket (14 inches).

In antiquity, water organs would have multiple sets of pipes and channels so chords could be played with a single key (Vitruvius, *On Architecture*, 10.8.2). Additionally, many organs have a register of multiple octaves. Due to the time and budget constraints of this project, the group decided that a single octave, tuned from equal temperament middle C to an octave above would be the best choice for the range of the instrument. Additionally, only one set of pipes was made, as making several channels of pipes was outside the scope of this project.

Each of the materials used in this project was carefully considered before it was chosen based on its cost, availability, and difficulty to use. In the original description from Vitruvius, almost every component of the hydraulis, including the water-holding parts, pump cylinders, plumbing, dolphins, pipes, and other parts, was made of bronze or iron. Because of the high price of metals and the difficulty associated with machining them, the group determined early on that making all the parts out of their original materials would not be feasible. Wood, 3D printing, PVC pipes, and buckets were substituted for metal in different aspects of the design. When the project was conceived, it was determined that wood would be used in the construction wherever possible because it was the cheapest and most readily available material. The decision to make the pipes from wood instead of metal stems from the fact that many modern organ pipes are made of wood. The internal geometry of wooden and metal pipes differ, so modern sources had to be consulted, although it is theoretically possible that wooden pipes were used when the hydraulis was first invented. Similarly, the bronze pistons for the pumps were replaced with wooden equivalents. The cylinders for the pumps were kept as metal because suitable metal piping was found in the BDW, and the metal would inherently have less friction than any wooden equivalent. A plastic five-gallon bucket and PVC piping from Home Depot were used instead of bronze funnels and piping because they were inexpensive reliable materials that were known to be watertight. The dolphins, check valves, and the caps for the organ pipes were 3D printed using PLA filament, as they had complex geometries that would not have been easy to construct out of a different material in the time frame allotted. To keep the hydraulis waterproof and airtight, this project employed different tapes, Flex Seal spray, and silicone sealant as equivalents to the resin that would be used in antiquity though these methods proved to be flawed. A larger plastic container was installed into the altar to simulate the bronze basin described by Vitruvius (*On Architecture*, 10.8.1). Though substitutions and modifications were made to the original design, each material and design element was chosen with an ancient equivalent in mind, and no major changes were made to the overall structure or function of the organ.

Primary Documentary Sources & Evidence

The primary sources that were used in this recreation of the hydraulis were excerpts from *The Ten Books on Architecture* by Vitruvius written around 20-30 B.C.E. and *The Pneumatics of Hero of Alexandria* by Hero of Alexandria written around 10-70. Both sources described the construction of the hydraulis in technical detail which was helpful in designing and constructing the organ. There were some key details missing, so modern sources had to be used to help fill in missing information. The most egregious lapses in information across ancient sources were measurements. Although the sources were highly detailed and specific with the overall inclusion of all the pieces and how each piece connected with its corresponding parts, both sources lacked almost any form of measurement for any of the parts. This included the sizes of pieces in relation to each other, as well as the general scale of the instrument. After examining various images provided in the ancient source materials, it was discerned that the organ was almost as tall as the average person, and a little over twice as wide. These approximations are supported by modern analyses of the organ. While pictures and qualitative descriptions proved helpful in getting a sense of the overall scale and general sizes of every piece of the organ, specific dimensions were selected so that the organ could be constructed and function properly.

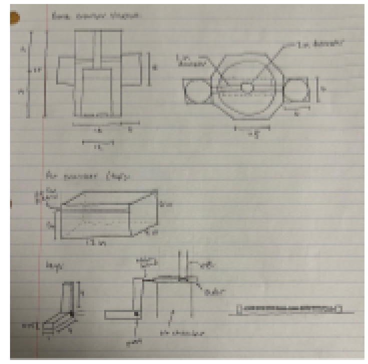
Additionally, ancient descriptions of the check valves, a critical part of the connection between the air pumps and water chamber, were incredibly vague or omitted entirely. The only possible mention of the check valves was by Hero when he wrote "when depressed, [the piston] opens the valve in the small box. By this means the box is filled with air from without, which the piston, when forced up again, will again drive into the hemisphere" (*The Pneumatics of Hero of Alexandria*, p. 107). Although this is likely a reference to a check valve, Hero does not elaborate on the function nor logistics of this device, instead opting to briefly describe their function in the context of the entire organ

Despite the substantial gaps in ancient sources, modern sources and personal engineering experience helped to fill in the gaps when creating the final design. Modern sources provided a litany of information that was missing from ancient sources, such as measurements and more up-to-date descriptions of all of the components of the hydraulis, including the check valves.

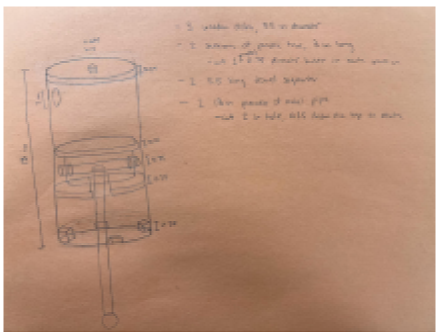
<u>Pre-Planning & Design</u>

Preliminary Sketches & Materials

The design process began with the examination of sources on the construction of the hydraulis, such as Vitruvius and various YouTube videos that better illustrated the mechanics of the different components. Initial designs for the organ were sketched out with the main


Initial drawings of water chambers, air chamber, keys, and cylinder

dimensions regarding the base structure, air chamber, keys, and cylinders. These drawings were used to estimate the quantity of wood and other needed materials such as Flex Seal, plumbing, and a metal rod. Many of the dimensions shown to the left were altered slightly based on the availability of materials. Because of the constraints of this project, wooden organ pipes were constructed in lieu of the metal ones used in antiquity (Vitruvius, *On Architecture*, 10.8.4). Dimensions for the wooden pipes were sourced from modern sources discussing the geometry of wooden pipe construction. (Giangiulio, n.d.). One octave with 13 keys was chosen starting from middle C. After construction of the altar and air chamber, a design was finalized for the cylinder and piston. The total cost of this project was $125.00. Additional materials, such as scrap wood, cotton, cloth, and 3D-printed components were sourced from the BDW with no additional cost.


Finalized drawing of cylinder and piston

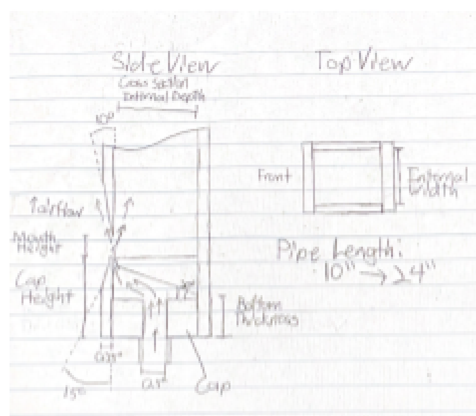
Construction

The initial approach to constructing the organ was to divide the project into components that could be completed independently by different group members and assembled at a later date. Geoffrey was tasked with designing and constructing the pipes, Annie focused on the keys and air chamber, and Julia and Taylor were responsible for the base structure of the organ and internal tubing. Nate focused mainly on research, but assisted with the construction of these elements as needed. During and after the Thanksgiving break, all group members contributed to the remaining tasks including constructing the cylinders, pistons, and levers as well as overall assembly and testing of the organ.

Pipes

Full octave of 13 pipes, starting with middle C

The construction of the organ pipes (see left) took place from mid-November to mid-December in the BDW. The construction of each pipe consisted of 3D printing the pipe cap, cutting and planing the plywood, gluing the pieces, cutting the pipe to length, and finishing each pipe. The dimensions of each pipe were modified from Raphi Giangiulio's wooden pipe organ (*Raphi Giangiulio's Homemade Pipe Organ*, n.d.). For each pipe, a cap was modeled using computer aided design and 3D printed in PLA plastic. The measurements for the pipe caps are different for each pipe, as each pipe needs to resonate at a different frequency. After the caps were printed, their internal depth measurements were used to mark the side planks on 0.25 in plywood that was between 2 and 3 feet long; the exact length varied as all the pipes would be cut to the final tuned length after being fully assembled. These strips were then cut out on the table saw, following the measurements exactly so the pieces would all line up. After two side lengths were cut for each pipe, they were lined up with the pipe cap to mark the width of the front and back planks, which were then also cut on the table saw. Once the four planks for a pipe were cut, the front plank was cut into two separate pieces: the upper reed portion and the lower



Drawing of pipe interior

portion which covers the cap. Each cap cover piece was cut to the cap height with the miter saw and a 15° angle was hand planed into the top of the cover. Similarly, the reed was formed by hand planing the bottom of the upper portion at a 10° angle. This is the part of the pipe that air flows over to make tones. Once all five wooden pieces were cut out, the inside faces of each plank were lightly sanded. Two wooden spacer blocks, the width of the pipe cap, were cut for each pipe on the miter saw to keep the walls of the pipe aligned during gluing.

Gluing setup process with clamps for one pipe

The gluing process was done in two stages. First, the pipe cap and side walls of each pipe were glued together. This step consisted of clamping the back plank to the workbench and applying wood glue to the back edges of the side walls and to the four sides of the pipe cap. These pieces were then put into place and clamped together to ensure a strong joint. The spacer blocks were added without glue in between the side walls to keep them parallel. Also during this stage, the cap cover was glued and clamped on top of the pipe cap. Once the glue dried for 30 minutes, the clamps were removed along with the spacer blocks. The second gluing stage secured the front plate with the reed to the front of the pipe. Glue was applied to the front edges of the side walls and the front plate was put on the pipe with the reed at the bottom facing outwards. Calipers were used to align the plate so that it was the correct distance from the cap cover. This plate was also clamped into place and allowed to dry for 30 minutes. When the glue had all dried, the clamps were then removed. This process was repeated for all 13 pipes.

To tune the pipes to the correct notes, the miter saw was used to cut the pipes to the correct resonating length. This length was achieved through trial and error; small amounts of the pipe were cut off and the pipe was tested after each cut with a tuner app to evaluate the pitch of the note produced. Once the pipes were all in tune, they were hand-planed and sanded to finish the surfaces. The inlet of each pipe was also sanded to create a snug fit with the upper air chamber.

Air Chamber & Keyboard

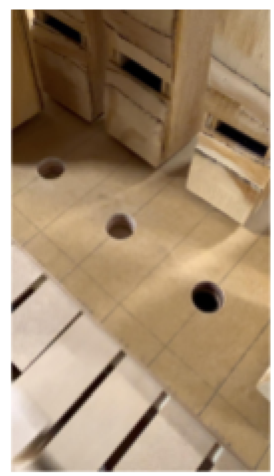

Unattached keys with holes for the metal rod

The keyboard was constructed starting in mid-November using a 10 ft piece of 1 by 0.75 in wood, which was cut into 26 pieces each 4.75 in long using the miter saw. Half of the blocks had holes drilled into them with a drill press to attach to the metal bar that holds the keys as a pivot point, and the rest of the blocks were glued upwards to form a static perpendicular lever that would be attached to the sliders. Hooks made from staples and pins were attached to the backs of all the keys. These were later clasped to the springs, which were found in the BDW. Thirteen springs of similar length were located, but some differed in spring constant resulting in tension varying across the keys. The air chamber (6 by 16 in) was built and later hand planed so that the front and back sides were slightly lower, creating a 3/16 in gap for the sliders. The walls of the air chamber were attached using wood glue. Afterwards, the keys were connected to the metal rod (15.5 in) and attached to the springs to the front of the air chamber using metal hooks. The keys were


Keys attached to the outside of the wind chest with springs

separated with washers to stay ⅛ in apart. Springs were placed in the holes of the two wooden attachment blocks on either side of the keys to prevent the metal rod from coming loose. Because the centers of the keys were only 1.125 in apart, the holes in the air chamber cover were staggered to create two rows of pipes. The front holes were 1.75 in from the front of the cover, while the back holes were at 4.75 in. These dimensions were based on the size of the pipes. The piece was sanded so that the pipes could fit snugly in the holes without needing to be glued. Afterward, 8 in. long sliders were cut using the miter and table saws with ⅝ in holes, varying in position depending on the location of the pipe hole. These fit behind every key to uncover the hole while the key is pressed. To stop the sliders from moving up and down, the pieces were connected with a small piece of string to account for the change in the height of the key as it is pressed down. These attachments were made with hot glue and small wooden strips. Initially, the separations between the sliders were done with staples, since the sliders kept getting caught on the nails. This was later replaced with small wooden pieces which better sealed the holes. An additional cover piece with holes was later added below the sliders with holes to minimize air escaping; the edges were also lined with cotton for a tighter fit.


Sliders being attached to the keys with spring (spacers have not been placed yet)

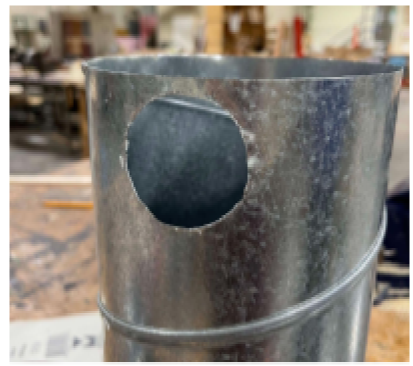

The hole in the top cover becomes uncovered when the key pulls on the slider

Cylinders & Pump Levers

Over Thanksgiving break, four wooden circles with a 5.75 in diameter were cut using a jigsaw to form the pistons inside the cylinders. Afterwards, four 3-inch tall wooden blocks were cut using the miter saw, which were spaced 3.5 inches apart and sandwiched between two of the

Wooden pistons being assembled with wood glue (before being wrapped in cotton and cloth)

circles with wood glue keeping the pieces together. A channel was cut in the bottom circle for the piston arm to extend downwards and swing as the lever was pumped. Additionally, a drill press was used to drill holes in the wooden separator blocks and the arm for a dowel to fit in between and form a connecting joint. The top disks were wrapped with cotton and cloth which was nailed and glued to the wood to form a tight connection between the piston and the inside of the cylinder. After, two 13-inch segments were cut with shears from a 6-inch diameter metal pipe to form the two cylinder pumps on the sides (see left). Each of these has a 1.5-in diameter hole cut from the side to attach to the pipes. These dimensions were selected based on the constrained distance from the floor and the fact that at least 7 inches of piston articulation was needed for the air. Dowels and wooden rods were cut and mounted together to form the lever arms. Afterward, holes were cut and drilled into the four supporting wooden blocks that acted as the main fulcrum for the levers. These were attached to the base structure with screws and wood glue. Additional holes were drilled into the centers of the levers and attached to the fulcrums with longer dowels. Afterward, 14 wooden pieces (approx. 5.5 by 6in) were cut and glued together to form the wooden outside cover that wraps around the metal cylinders. Two holes were drilled into the top covers for the dolphin check valves and rubber rings were hot glued to the inside so that the



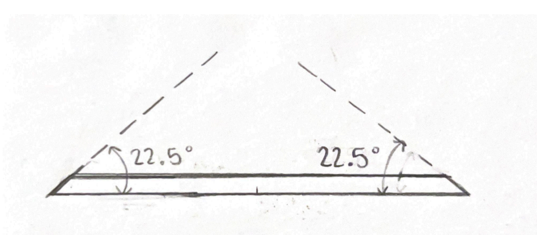
Hole in metal cylinder for piping attachment

Cylinder attached to side of alter without wooden covering rubber stoppers used in the check valves formed a tighter fit. A dolphin CAD model was modified by adding standoffs and a hole for the string that tied to the dolphin's nose. Rubber stoppers were attached to the string, which had to be melted slightly to form the proper conical shape. They were then covered in grease to form an airtight seal with the rubber ring, while allowing for the air to be pulled inside the organ while the piston is being pulled downwards. When the piston is pulled down, the lower air pressure pulls the rubber stopper, opening the air valve. Wooden caps were siliconed to the tops of the cylinders, and rubber rings were fastened to the holes on the sides to create an airtight seal to the PVC pipes. The pipes were later directly secured to the pipes to the cylinders with hot glue and tape.

Fully constructed cylinder, lever, and delphini check valve system

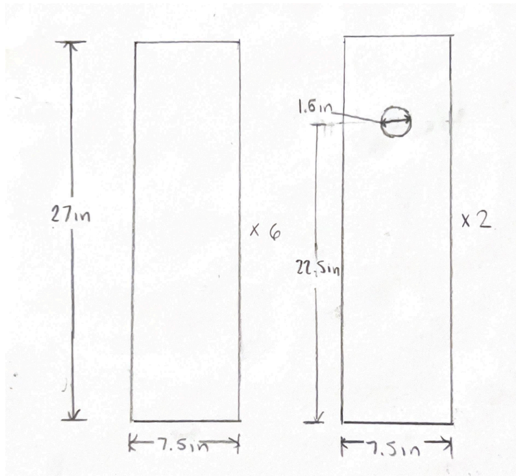
Octagonal Base Structure, or "Altar"

The octagonal base, or "altar", was constructed of 8 wooden panels cut into trapezoidal prisms. The schematic below depicts the cut angle of 22.5°, which ensured the panels laid flush when adhered together in an octagon shape.



Schematic A: The cross-sectional view of the wooden panels, cut at a 22.5° angle.

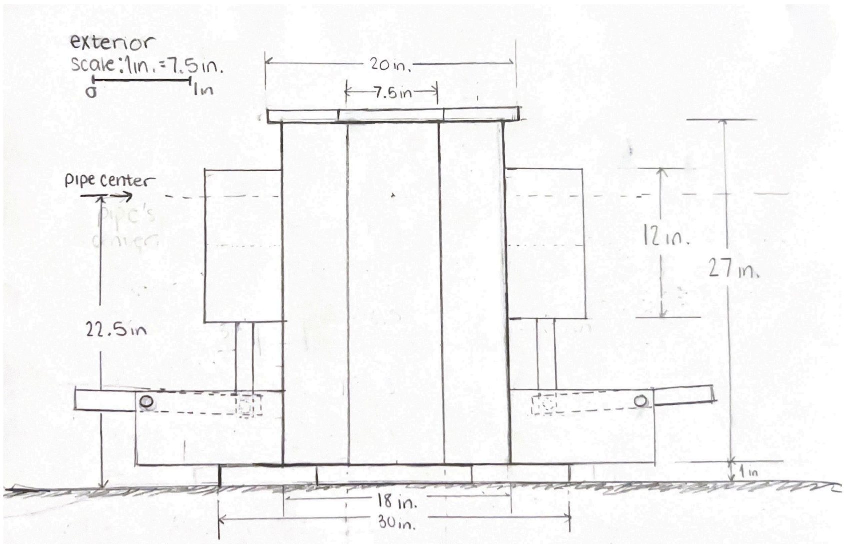
The panels were cut to a height of 27 in. and an exterior width of 7.5 in. (the cut angle resulted in an interior width of approximately 7 in.). In 2 of the panels, outlet holes were filed and drilled for the pipes connected to the pump systems; one panel did feature a small drainage hole, which was later filled as it was unnecessary.



Schematic B: Measurements for the wooden panels; 2 panels (right) with outlet holes for the PVC pipes attached to the pump systems.

To form the altar, the panels were glued (angled sides) together, with the 2 “outlet” panels positioned directly across from each other. The panels were laid flat, glued and rolled up, and duct taped into the octagon shape. Liquid Nails construction adhesive was used to glue all of the wooden pieces of the base together. After the glue had dried, Flex Seal was sprayed onto the inside of the base to make the inside water-resistant. This was effective and water did not seep into the wood itself. At first, silicone sealant was used to seal and reinforce the joints between the wooden pieces of the base and all of the pipes, as it was advertised as waterproof. During trials, water seeped through small gaps in the bottom of the organ. It was deduced that the sealant could not properly adhere to the wood. Thus, a plastic bucket was purchased to line the inside of the organ to ensure it was watertight. The silicone did keep the connections between the pipes and buckets water/air-tight but the joints had to be removed to add the bucket and ended up being replaced with electrical tape due to time constraints.

An octagonal lid with side lengths of 7.5 in.was constructed featuring a hinge that provided access to the altar's interior. The lid also had a 2-in. outlet hole to connect the PVC pipe to the keyboard. The bottom octagon featured a diameter of 30 in., to adequately support the structure's size. Schematics C depicts the exterior elevation of the altar when viewed from the front.

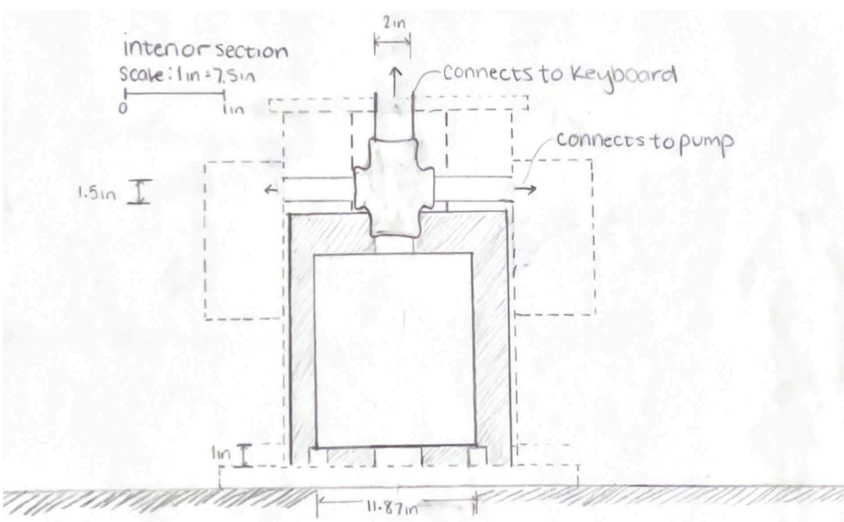


Schematic C: Exterior of the organ altar, drawn at a 1 in.=7.5 in. scale.

Plumbing & Water Chamber

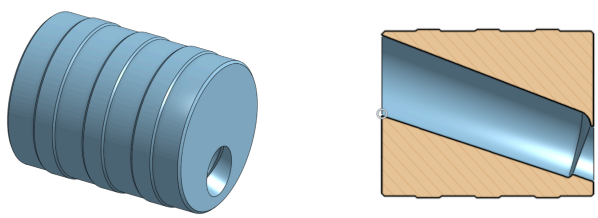
For the organ to generate the air pressure to blow air through the pipes, a water chamber was required. Air would be pumped into this chamber and displace the water so that the air being released through the pipes would have a constant air pressure and could sustain long notes. It was necessary for the plumbing to connect the air chamber, water chamber, and air pistons. Schematic D illustrates the plumbing system and interior of the organ. To ensure the proper function of the organ, all components of the plumbing water chamber needed to be both watertight and airtight, and there had to be valves so that air could not flow out of the organ at the locations of the pumps.

A five-gallon plastic bucket was selected to function as the water chamber since it was prefabricated and would eliminate the need to design and construct the chamber. A 2-inch diameter PVC pipe was selected to connect the bucket to the air chamber and a 1.5-inch diameter PVC pipe was selected to connect the cylinders to the internal central pipe. These diameters were selected because of the measurements of the cross-pipe fittings available at Home Depot. First, a 2-inch diameter hole was cut in the bottom of the five-gallon bucket using a 1.5-diameter hole saw. The hole size of the hole was increased using metal shears, a box cutter, and sandpaper until the 2-inch diameter pipe could fit snugly into the hole. The lengths of the pipes were not determined in the initial design process but were instead measured to the appropriate length once the base of the organ had been constructed. The PVC pipes were cut using the miter saw, and later on Japanese pull saw after the BDW monitors scolded the group for cutting PVC pipes with power tools. Initially, all of the plumbing was assembled using silicone sealant, but these joints were later replaced with electrical tape. Inside the organ, the bucket was elevated using 1-inch tall blocks of acrylic so that water could flow freely as air was pumped into the organ.



Schematic D: Interior section of the organ altar, drawn at a 1 in.=7.5 in. scale. The shaded region represents the additional bucket added for waterproofing purposes. The pipes connect the Home Depot bucket in the center of the organ to the pumps and keyboard.

The tubing that connected the pumps to the main air chamber needed check valves to be installed so that air could not leak back into the cylinders. Because traditional check valves could not be used in this application due to their large size and high cost, smaller check valves were designed and 3D printed as shown in Schematic E. These check valves consisted of a cylinder that was the diameter of the interior of the PVC, with a small channel through it, and a ball bearing that sat in the channel, creating a seal when air is blown back through it. These valves were then press-fitted into the PVC pipe.



Schematic E: 3D printed check valve and cross section. The valve is cylindrical with a circular channel cutting diagonally through it so a ball bearing can slide through it, weighed down by gravity.

Testing & Adjustments

As indicated in the presentation given on December 4th, all parts of the organ functioned properly independently of one another. Each pipe was tested manually by blowing through the inlets, and the pumps were tested to ensure they moved air. On Tuesday, December 10th, all parts of the organ were assembled and on the first trial with water, there was significant leakage out of the base of the organ. The organ was quickly drained, which proved that the designed drainage system was very effective, so alternative approaches to keeping the organ watertight could be explored. Since there was not enough time to reapply silicone and let it cure, it became apparent that something would need to be added to line the inside of the organ. This meant that the internal plumbing had to be removed from the organ and that all of the joints that had been previously sealed with silicone had to be ripped apart, which revealed that they were not very airtight and would have led to the organ not being audible.

After experimenting with various plastic trash bags, which kept ripping and leaking, it was suggested that a plastic bucket of some sort be used to line the inside of the organ. While this would incur an additional cost and meant that the organ would have to be manually emptied instead of using the drainage system, the group felt that it was most important to ensure the organ was watertight. A 20-gallon outdoor trash can was purchased during a 10:30 pm trip to Walmart. A few inches were cut off of the top using the Japanese pull saw so that the container would fit inside the organ.

After reassembly using electrical tape, another trial was conducted. The lack of water leakage proved to be a small victory, but the organ was not yet audible, despite all of the air that was being pumped through, which indicated air leakage. The inside of the organ was examined while air was being pumped through to locate potential areas of leakage and the joint between the pipe and the air chamber was identified as the main problem. The organ was then emptied so that this and several other minor issues could be addressed.

The O-ring used to seal the pipe to the air chamber was attached to the pipe, using silicone sealant, at a specific height to eliminate the vertical movement that was leading to the air leakage. Additionally, after being emptied, it became clear that a ball bearing had fallen out of one of the check valves, rendering it ineffective. To fix this issue, pipes were removed from the cylinders so that the check valves could be accessed and repaired. A hairdryer was used to melt and bend the plastic so that the bearing could no longer fit through the hole in the valve. This was hypothesized to be stronger than the previous method of containment, which was a piece of wood superglued over the opening. The pieces of acrylic used to raise the bucket were secured to the bottom of the organ using hot glue. All excess dried silicone from the initial assembly was removed from the pipes to ensure that the electrical tape could form the best seal possible. Work on the organ stopped at 4 am.

On the morning of the presentation, the appropriate PVC pipes were joined to the orange bucket and cylinders with hot glue and tape in the BDW, but there was not enough time to conduct another trial before the final showcase.

Transportation and Setup

Due to the size of the organ and the pouring rain, the organ had to be transported in separate pieces. The pipes and cylinders were brought over on foot in trash bags, while the base of the organ, lid, and air chamber were covered with shower curtains and brought over on a cart that had been borrowed from the BDW. Upon arrival at Rhode Island Hall, the basin of the organ was filled with approximately 10 gallons of water from the water fountain and bathroom sink. Then all of the plumbing was placed inside the organ and the joints were sealed with electrical tape. A thin rope was tied around the organ to secure the cylinders in place. Finally, the air chamber and pipes were placed onto the top of the organ. In total, two hours were required for the transportation and assembly of the organ.

Reflection & Conclusion

Final Demonstration & Operation

The organ was playable at the final showcase. First, a full scale was played to demonstrate that all of the pipes produced the correct notes. “Mary Had a Little Lamb” was also played to demonstrate the musicality of the instrument. Several other melodies were improvised to demonstrate that multiple notes could be played at the same time. At some point during the demonstration, the air was pumped forcefully enough that one of the check valves was dislodged and fell into one of the pumps. This led to water getting sucked into the plumbing and eventually the air chamber, meaning that the organ could only emit notes that were in time with the pumping rather than sustained notes. Despite minor technical difficulties, a successful working hydraulis was created.

Overall Construction Process

Although very meticulous and precise, the construction and tuning of the pipes was a smooth process. Initially, it was thought that tuning the pipes to accurate pitches was going to be a very difficult task that would require several iterations, but the pipes were the first part of the project to achieve functionality. On the other hand, there were several aspects of the project that proved to be more difficult and time-consuming than initially anticipated, the most surprising of which was drilling holes. Large holes had to be drilled in the bucket, lid, and sides of the organ to account for the inner tubing of the organ. Unfortunately, the BDW did not have the appropriate arbor to connect the correct hole saw bit, so a smaller hole had to be cut and then the hole had to be sanded and filed to the appropriate size. This was a tedious process and the holes ended up being misshapen rather than perfectly circular. A jigsaw was also used for some holes, but had similar issues producing a hole of the correct shape and size and ended up requiring sanding and filing as well. Waterproofing also proved to be a very significant challenge, which was not anticipated since the Flex Seal and silicone sealant are specifically designed for waterproofing and are successfully used in many modern-day bathrooms. Furthermore, several aspects of the organ needed to be revised as the original forms were not airtight enough. In particular, the keyboard and upper air chamber required modifications for them to hold air well enough to produce notes. These difficulties highlight the precision and engineering skills of antiquity that allowed for the creation of such a complicated instrument.

Though the tools and materials available were quite different from those available in antiquity, every method and component of this organ's design could have been constructed in ancient Greece or Rome with equivalent materials. Electric tools such as miter and table saws were used in this project, but in the ancient world, hand tools could easily do the same work/ Similarly, plastic and wooden parts replaced certain bronze pieces, but they did not impact the function. The final for this project was simplified from antiquity, and as such, could be easily reproduced with the tools and materials available at the time.

Almost every part of the construction process ended up being more time-consuming than anticipated, which is why testing did not occur until the night before the showcase. Due to these delays, group members had to work on parts of the construction process that were outside of their initially assigned tasks so that the entire project could come together. Fortunately, the group had access to a car, which made it very easy to acquire materials and Home Depot and Walmart. This was especially helpful when additional materials needed to be purchased throughout the construction process as the design evolved. The project also relied heavily on scrap wood from Annie's garage and the BDW. Even with access to a design workshop and many free materials, the project was behind schedule and over budget, as was the case with many construction projects in antiquity.

Each group member had a unique skill set and diverse perspective which was essential to the completion of the project. Nate's passion for research and history sources helped ensure that the final design was as close to antiquity as possible. Although it was not played in full, it should be noted that Nate took the initiative to find a song from Ancient Greece, the Song of Seikilos, and arrange and transpose it for the organ created in this project. This added another level of authenticity to the project. Taylor is pursuing an architecture degree and was able to construct accurate scale drawings and make precise measurements and cuts which proved to be indispensable when working with octagonal shapes. Julia has logistical and organizational skills that helped keep the project on track and make sure that all aspects of the design were completed and materials procured in a timely and efficient manner. Annie's critical thinking and prototyping skills were crucial in the successful execution of all moving parts of the design, including the pistons, keyboard, and cylinder lids. Geoffrey has an extensive woodworking background and knowledge of almost every tool in the BDW. This meant he had the expertise necessary to craft the pipes and help group members find more efficient methods of completing other construction tasks.

Ancient sources inspired the design from a macro perspective. These sources informed the overall shape of the organ and the parts used in this project. The lack of general measurements present in ancient sources led to many of the specifics of the project being improvised or based on modern sources. For instance, impromptu solutions to issues such as air and water leakage required more modern materials since there was no access to the expensive and time-consuming methods used in antiquity. This is the reasoning behind the most obvious deviations from the ancient source materials, including the heavy use of duct tape and the use of the plastic trash can in the water chamber. The final organ is consistent with the high-level structural descriptions from antiquity while using the same principles used in the ancient hydraulis to produce sound.

Social Context Revisited

When describing the hydraulis, Vitruvius described most of the technologically important parts of the device as made of bronze, including the cistern (*On Architecture*, 10.8.1). During the construction of this hydraulis, alternate materials for the cistern: initially wood, but in the end, plastic. These changes had to be made due to an inability to access sheets of metal, such as bronze, largely due to financial constraints. What this demonstrates about the hydraulis construction process from antiquity is how skewed it was to the upper class. Even with modern resources and technology, creating the hydraulis on a budget was very difficult, illustrating the incredibly high costs and large amount of resources that must have been necessary to create the instrument.

A similar conclusion can be drawn from the construction process itself. Throughout history, the mechanics and construction process of the hydraulis went largely misunderstood. Many individuals produced inaccurate explanations of the instrument and how it was built (Mckinnon, p. 7). While building and showcasing this version of the hydraulis there was similar confusion. Many people, after seeing the instrument, either dormant or while it was producing sound, were unable to determine the way the instrument worked or misunderstood the purpose of different parts. Even in a modern university setting in which most people are far more educated than the average individual in antiquity, the hydraulis is still not an intuitive device. This further suggests the idea that the comprehension and construction of the hydraulis was for the highly educated, and therefore the upper class.

Despite the stark divide in who was able to finance, create, and understand the instrument, the hydraulis still largely appealed to and was used for, the general public through its use in large public spectacles and theatres (*Aetna*, p. 387) (Morgan, 2022, pp. 290-291). This heavy contrast was also shown through the demonstrations, in which the music was able to be enjoyed and appreciated by individuals regardless of their understanding of, or participation in, the construction process. Even emperor Nero understood this contrast when he attempted to gain favor from both the upper and lower class through his use of the hydraulis, as he knew the instrument appealed to both groups (Morgan, 2022, pp. 285, 296). Overall, these traits and uses are what gave the hydraulis the ability to foster connections between the social classes of antiquity and create social change, making the hydraulis far more than just an instrument or a demonstration of technological growth.

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