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Mechanical Engineering CAL POLY

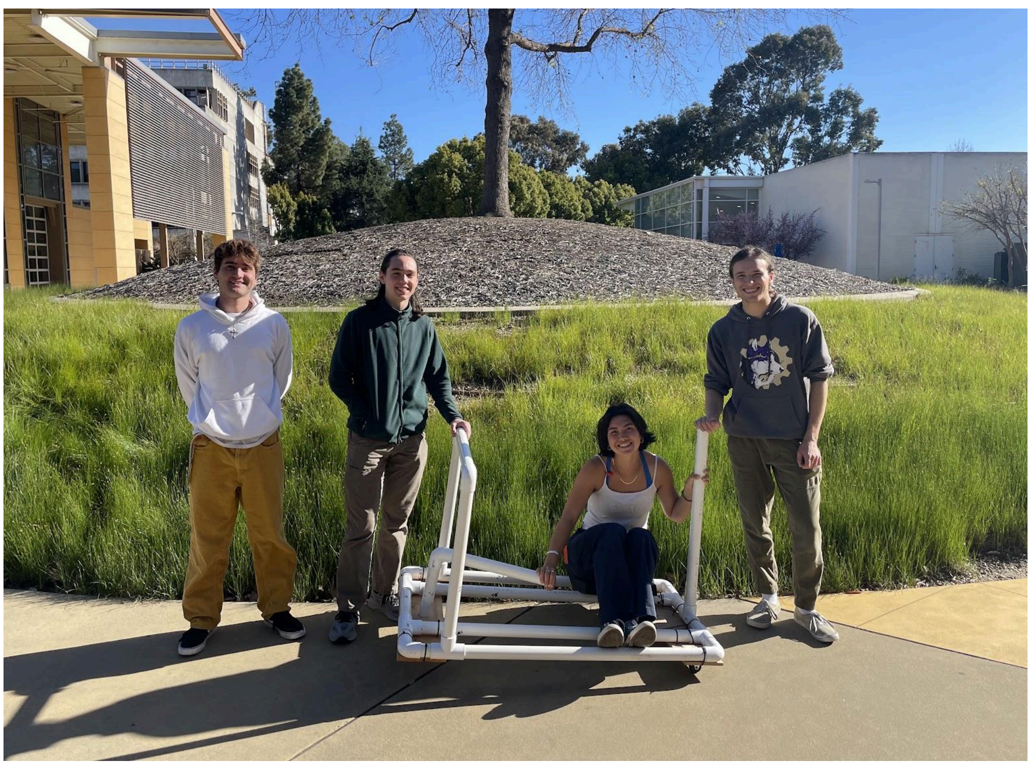
MEMORANDUM

3/15/2024

TO: Dan Castro, Professor, Mechanical Engineering
FROM: The Pirate's Posse
Alanna Perrin, Colin Moore, Garrett Kunkler, Joseph Hovanesian

SUBJECT: ME 328 Kart-Racing Scooter Design Project - Final Report

The Sailless



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Design Overview and Relevant Background

This vehicle that was designed over the course of the past 5 weeks is called The Sailless. The main objective was to design a PVC vehicle that could be pushed from behind. It must fit within a 2.5’ by 6’ rectangle and the vehicle needed to be made of at least 50% PVC piping. At the beginning of the process the budget was set to be $150 dollars, and the cart was designed for a 140lb, 5’8” rider.

Figure 1: Garrett demonstrating The Sailless’ seating configuration

The Sailless works similar to a small boat. The rider sits on the front corner of the cart near one of the two rigid caster wheels. To steer, the rider uses a tiller to rotate the third and final caster wheel. To stabilize themselves, the rider also can hold onto a “mast” attached to the front of the base. Another person is required in order to propel the cart forward. Based on Figure 1, a pusher would lean into the horizontal push bar on the left and the cart would move to the right.

Primarily designed for sailing enthusiasts, it may not be suitable for those with severe balance issues or significant upper body strength limitations. Due to the seating arrangement on the side of the cart, it helps to have enough core strength to maintain the center of balance within the triangular wheelbase. During construction, challenges may arise when integrating the tiller steering mechanism or attaching the wood to the PVC pipes. The wood block attached to the lower end of the tiller is held onto the slip hub through an interference fit. This could easily be sanded down too far, which would make the rear wheel have a chance to rotate free of the tiller or even fall off when a bump is hit. Potential improvements are discussed further in this report. When riding this cart, the rider should take care to stay balanced on the cart. The steering can be jarring at first and sharp turns can cause the rider to lose balance and fall off. They should also stay off of roads or sidewalks with large cracks that can jolt the cart and break the zip ties securing the wood to the PVC frame. Before riding, it is also important to make sure the tiller is set up properly so that the bearing is supporting the load.

Drawings and Assembly

See Figure 2 for the list of materials used for this project. The initial cost of the supplies was around $142, but some supplies were purchased that were not needed that were originally planned for in the initial design. These were returned to reduce the actual price to around $122. The PVC pipe segments and fittings are shown in an assembly drawing attached at the end of this report. In Figure 2, all PVC components are 1.5” PVC pipe. 30’ of pipe was purchased in total, and the remainder after messing up a few cuts, was the perfect length for a mast. A rough length that can be expected for this part is 3’.

Figure 2: Materials List

Item	Amount
90° Elbow PVC Fitting	7
Tee PVC Fitting	7
PVC Slip Hub	1
46” Pipe Segment	2
40” Pipe Segment	2
24” Pipe Segment	3
18” Pipe Segment	1
12” Pipe Segment	2
5” Pipe Segment	2
4” Pipe Segment	6
Front Wood Piece (9” x 28”)	1
Back Wood Piece (12” x 28”)	1
0.5” Wood Screws	36
2” Rigid Caster Wheel	2
3” Rigid Caster Wheel	1
Zip Ties	1 Packet
Thrust Bearing (2” inner diameter)	1

The design is fairly simple to construct. First, PVC pipes are cut and assembled into the configuration shown in Figure 3, as well as in the assembly drawing. For the front wood piece, the two 2” diameter caster wheels were screwed onto each corner. For the back wood piece, a single 2” diameter hole was drilled out for the vertical tiller piece. This hole was drilled as close as possible to the outer diameter of the PVC pipe without causing excess friction. To attach both wood pieces, holes were drilled as necessary to slip zip ties around the base in multiple places.

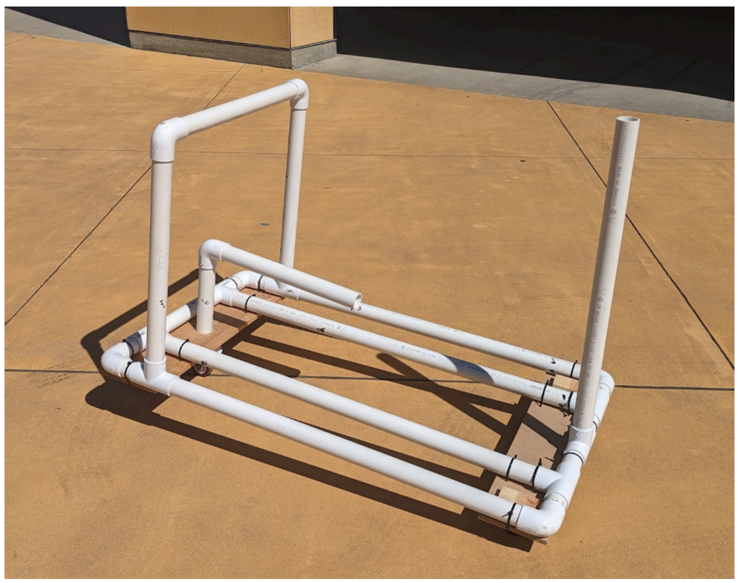


Figure 3: Full Assembled PVC Pipe Cart

The hardest part of construction was making the tiller. Since the slip hub found was much larger than the outer diameter of the PVC pipe, an adapter was made out of an approximately 6” x 6” x 3” piece of scrap wood. This involved drilling a hole for the PVC to slip into, cutting and sanding the outside of it to a circular shape, and using a router to make a groove for the thrust bearing to sit in. Once the PVC was screwed in place, a shim was placed inside the slip hub before pushing the adapter into the slip hub for an interference fit. Then the caster wheel was screwed through the bottom and the tiller was finished.

Figure 4: Detailed pictures of tiller mechanism separate (right) and in-place (left)

Calculations and Modeling

A design safety factor of 2 was chosen based on a yield strength for PVC of 7000 psi and a 140lb rider. A factor of safety of at least 2 ensures that the PVC push cart has double the strength needed for normal use, enhancing safety and reliability. It accommodates variations in material properties, dynamic loading conditions, and factors that may not have been considered in our calculations. Using the hand calculations along with the FEA model, 1.5” PVC pipe was found to satisfy the chosen factor of safety. Based on the initial hand calculations attached to this report, the actual safety factor was closer to 2.3 for the abuse case and 4.6 for the normal use cases. These use cases are:

Normal Case 1: Cart pushed on flat ground
Normal Case 2: Cart pushed up a 10° incline
Abuse Case: Rider jumps onto the cart, doubling the effective weight

Normal Case 1 was modeled in Solidworks to verify the hand calculations. The two points of concern were the point of max moment on the lengthwise beams and the joint where the push bar connects with the base. The applied weight is shown in Figure 4 to have a maximum stress of 981 psi and the push bar is shown in Figure 5 to have a maximum stress of around 367 psi. The deflection was also analyzed to make sure that the cart wouldn’t bottom out, and this is shown in Figure 6.

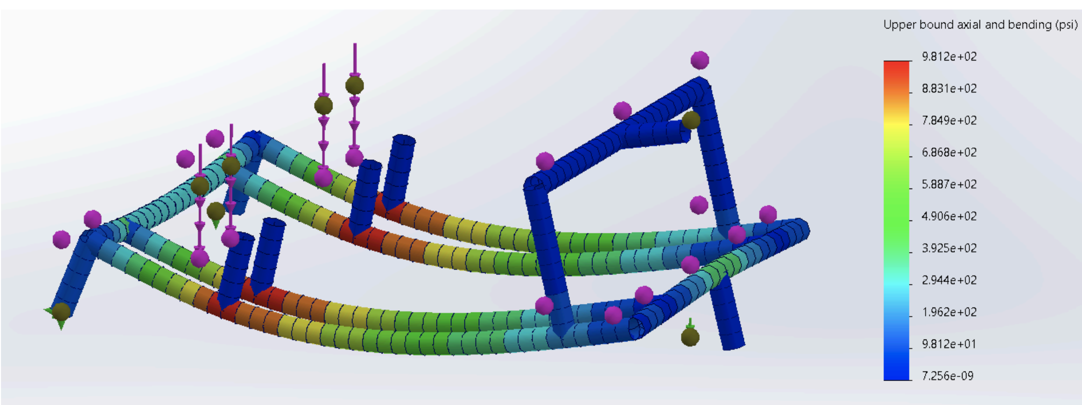


Figure 4: FEA axial and bending stress plot for 1.5” diameter PVC pipe (σ_{max} = 981 psi)

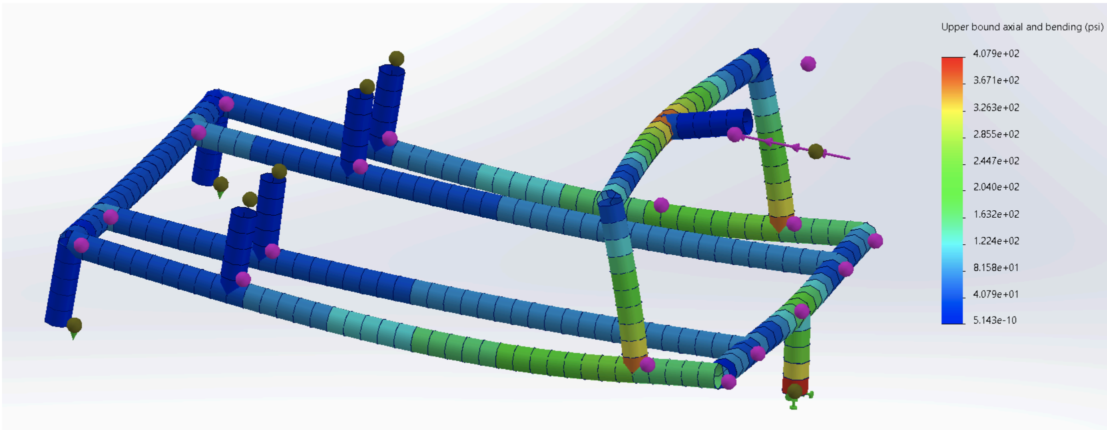


Figure 5: FEA axial and bending stress for push bar load ($\sigma_{max} \cong 367$ psi)

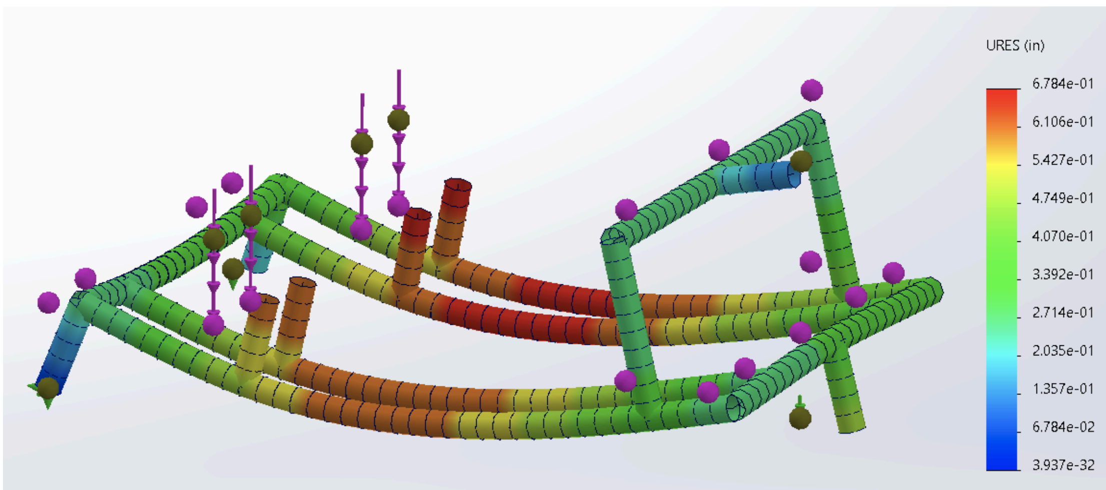


Figure 6: FEA deflection plot for 1.5” diameter PVC pipe (y_{max} = 0.67”)

The hand calculations also confirmed that the maximum stress would be along the 4 ft long side. In these hand calculations the maximum stress in this member was calculated to be 1017 psi which is pretty close to the value attained in the FEA study. Generally, the hand calculations for the maximum stresses were slightly larger than our FEA results. This further raises the factor of safety to 7000/981.2 = 7.1. This shows that our design is very unlikely to fail due to the PVC being overloaded.

The thrust bearing will also not be a point of failure. The supplier rated its maximum dynamic force capacity at 8408 lb, which even with its implied safety factor is much higher than the cart would ever be expected to experience.

Deflection Measurements and Other Testing Results

As discussed above, the main concern was deflection in the 4'-long lengthwise beams. From the FEA results, the maximum deflection was 0.67" slightly behind the rider. To measure the actual deflection, a ruler was used to measure the height off of the ground with and without a rider weighing around 140lb. The result of this testing was a deflection of 0.6", as documented in Figure 4.

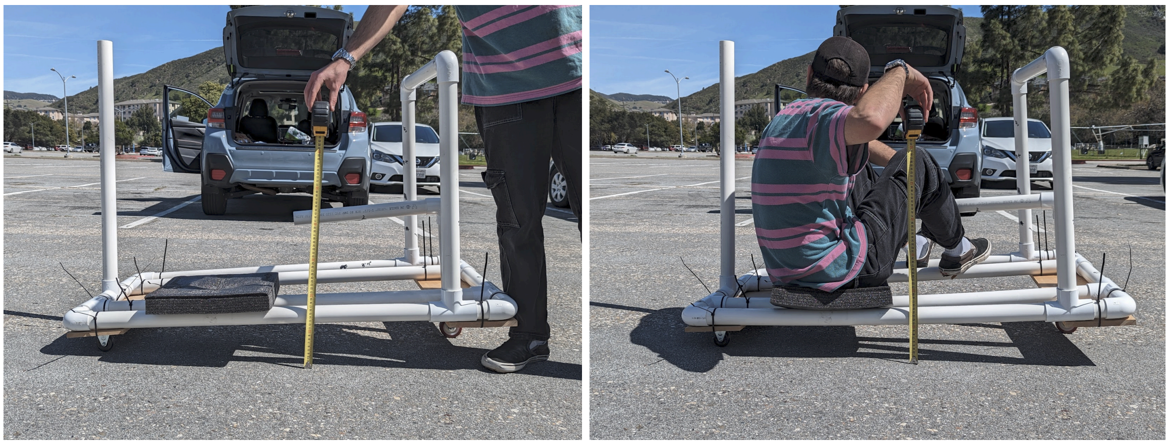


Figure 4. Deflection measurement setup with 140lb rider

Compared to the FEA model, there were a few notable differences. First, the back wheel with the tiller has been shifted forward by 4.75". This reduces the deflection by a little bit since the distance between the front and back wheels is shorter. Second, most of the rider's weight is concentrated on one side of the cart, which would increase the deflection on the two beams on that side. The wood pieces on the front and back do distribute some of this load, but the difference between the right and left side is clearly noticeable. With all of these factors together, the deflection is actually very similar to the 0.67" deflection that the FEA predicted, with a 10.4% error. This number is smaller than expected, considering how many simplifications were made when modeling.

Recommendations for Improvement

When designing and building this cart, there were some challenges that were overcome, and potential improvements arose as well. The overall stability and structural integrity of the wheel bases. Due to the budget constraint, larger wheels were too expensive. The larger wheels would've allowed for the cart to traverse sidewalks with larger cracks and gravelly asphalt without shaking. Preferably wheels that have a diameter of around 4" or 5" on the front and slightly smaller in the back would level the base and make it more comfortable to ride. Another improvement related to the surface conditions of the ground would be replacing the zip ties with u-bolts. A heavy rider and the jolts from hitting bumps or cracks in the sidewalk caused the zip ties to break many times during test rides.

Y-shaped fittings for 1.5" PVC pipe were hard to find, but they would make it easier on the pusher to maintain an efficient pushing angle, and would reduce bending stresses in the push bar. In this original cart, the push bar deflected downwards and forward when used. If future carts had the push bar protruded back at an angle towards the pusher, sort of like a stroller, it would also improve the pusher's ability to slow the cart down in case of emergency.

There are two more improvements that can be made that focus less on structure. The first is attaching the foam padding to the cart. The padding is nice for comfort, but it currently can be awkward to place and sit on without it sliding off. Zip ties or rope would both be good options for this. The second would be to attach a sail connected to the front "mast", the base, and the push bar. While it would reduce visibility of the rider, if there is a strong enough breeze, the need for a pusher could be temporarily eliminated.

Some recommendations for those building the Sailless in the future. Planning out the lengths of each PVC pipe that need to be cut can be done before cutting occurs. This helps save time and reduces risk of cutting the wrong length. Also, attaching the rear wheel to the base of the tiller is challenging, and is restricted by the parts available. Taking stock of different methods while shopping for the rest of the materials works to overcome this challenge. This way the project doesn't need to be set back if a specific part is needed for the tiller that can't be found while shopping.

Even without these changes, this cart is extremely fun to ride with its unique steering mechanism and seating arrangement. We learned a lot about the design process while prototyping this design. We got to practice using hand calculations to check FEA results and find the safety factor based on different use cases. It was also a great opportunity to get comfortable being in the machine shop and using the many tools at our disposal.

3 different cases

$S_y = 7000\,psi$ (PVC)

$n_d = 2.0$

Case 1: Flat ground and pushed

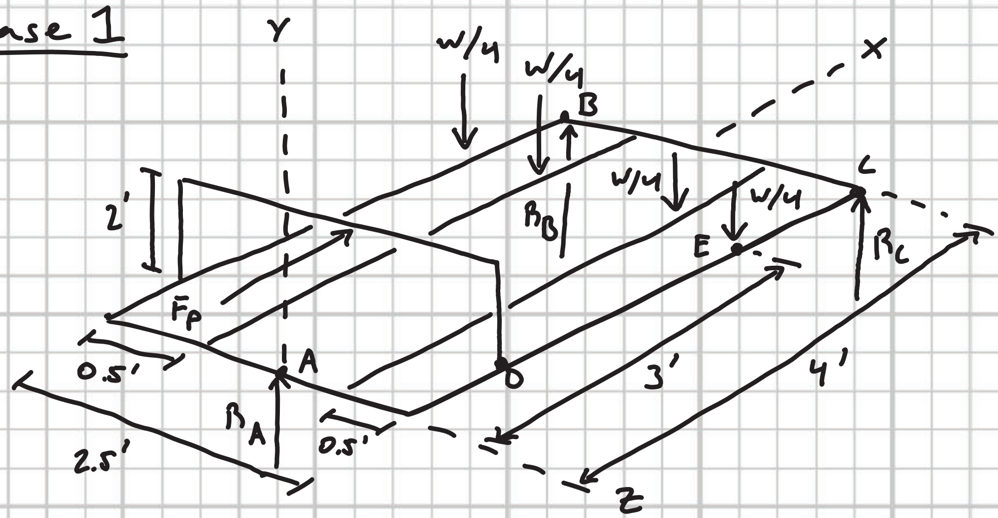
Case 2: 10° incline ($W_y = W\cos 10°$)

Case 3: Rider jumps on ($W_J = 2W$)

We are conserned about stress at 2 locations:

1) Push bar connection (D) 2) Application of weight (E)

Case 1



$F_p = 20\,lb$

$W = 140\,lb$

All pipes are 1.5" ID & 1.9" ID ($S_y = 7000\,psi$)

$(\sum M_z)_A = 0 = -W(3') + (B_B + B_C)(4')$

$B_B + B_C = \frac{3}{4}W = \frac{3}{4}(140\,lb) = 105\,lb$

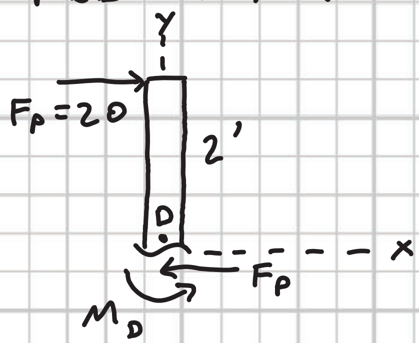
$B_B = B_C = 52.5\,lb$ by symmetry

$\sum F_y = 0 = B_A + B_B + B_C - W$

$B_A = W - B_B - B_C = 140\,lb - 52.5\,lb - 52.5\,lb$

$B_A = 35\,lb$

FBD: Push Bar

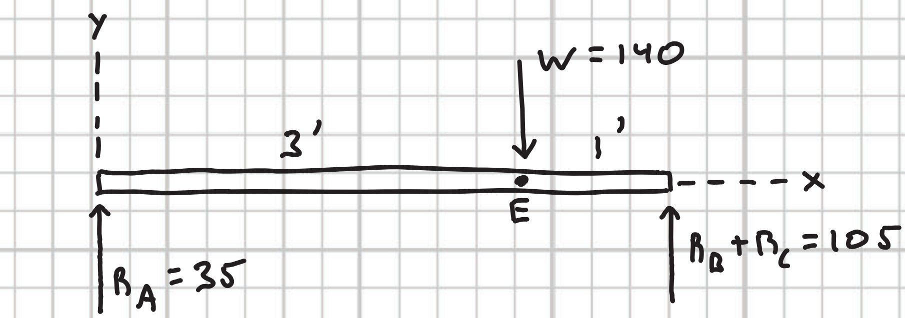


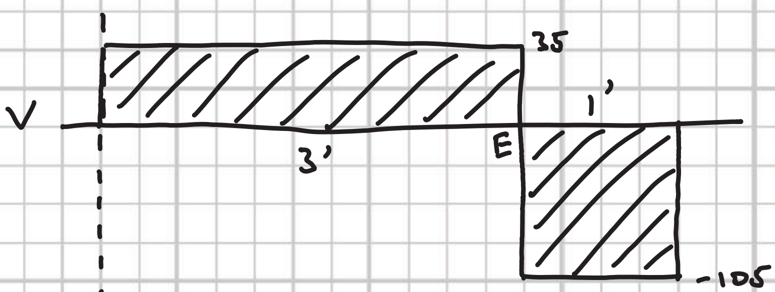
$$M_D = F_p(2') = (20lb)(2') = 40lb \cdot ft$$

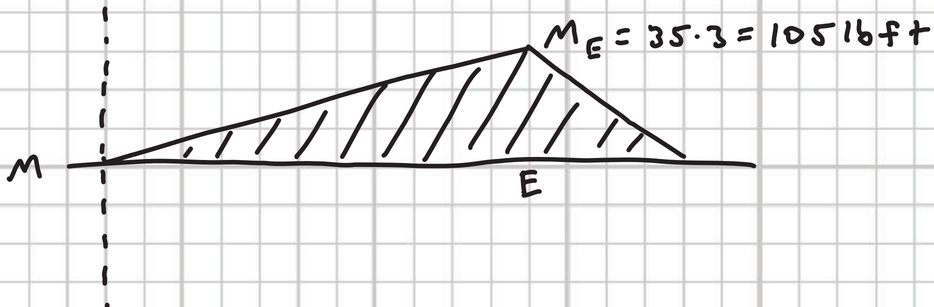
$$\sigma_D = \frac{M_D c}{I} = \frac{(40lbft)(1.9'')}{2\frac{\pi}{64}(1.9''^4 - 1.5''^4)} = 1165psi$$

$$n_s = \frac{S_y}{\sigma_D} = \frac{7000}{1165} = 6.0 > n_d = 2.0$$

FBD: 4' long members



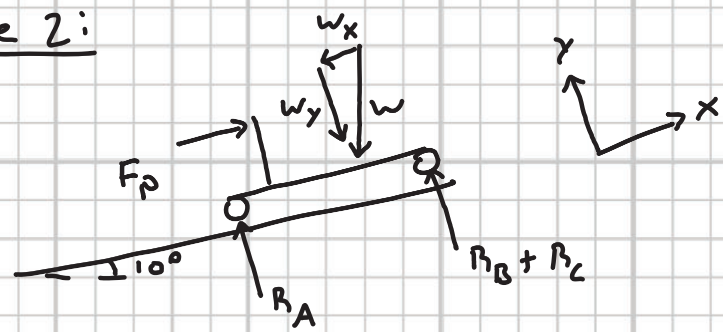




$$\sigma_E = \frac{M_E c}{I} = \frac{(105lbft)(1.9'')}{4(\frac{\pi}{64}(1.9''^4 - 1.5''^4))} = 1530psi$$

$$n_s = \frac{S_y}{\sigma_E} = \frac{7000}{1530} = 4.6 > n_d = 2.0$$

Case 2:



$$\Sigma F_x = 0 = F_p - W_x$$

$$F_p = W\sin 10° = 140\,lb \cdot \sin 10° = 24.3\,lb$$

Y-direction is identical besides a scaling by $\cos 10°$

$$R_A = 35\,lb \cdot \cos 10° = 34.5\,lb$$

$$R_B = R_C = 52.5\,lb \cdot \cos 10° = 51.7\,lb$$

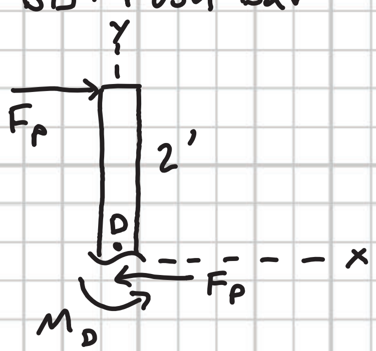
Similarly, M_E is also scaled by $\cos 10°$

$$M_E = 105\,lb \cdot ft \cdot \cos 10° = 103.4\,lb$$

$$\sigma_E = \frac{M_E c}{I} = \frac{(103.4\,lb)(1.9'')}{4\left(\frac{\pi}{64}(1.9''^4 - 1.5''^4)\right)} = 1507\,psi$$

$$n_s = \frac{S_y}{\sigma_E} = \frac{7000}{1507} = 4.7$$

FBD: Push Bar



$$M_D = F_p(2') = (24.3\,lb)(2') = 48.6\,lb \cdot ft$$

$$\sigma_D = \frac{M_D c}{I} = \frac{(48.6\,lb\,ft)(1.9'')}{2\frac{\pi}{64}(1.9''^4 - 1.5''^4)} = 1416\,psi$$

$$n_s = \frac{S_y}{\sigma_D} = \frac{7000}{1416} = 4.94 > n_d = 2.0$$

Case 3:

Use impact force 2W as weight

$W = 2(140 lb) = 280 lb$

FBDs are the same as Case 1 besides W

M_E is doubled: $M_E = 2(105 lbft) = 210 lbft$

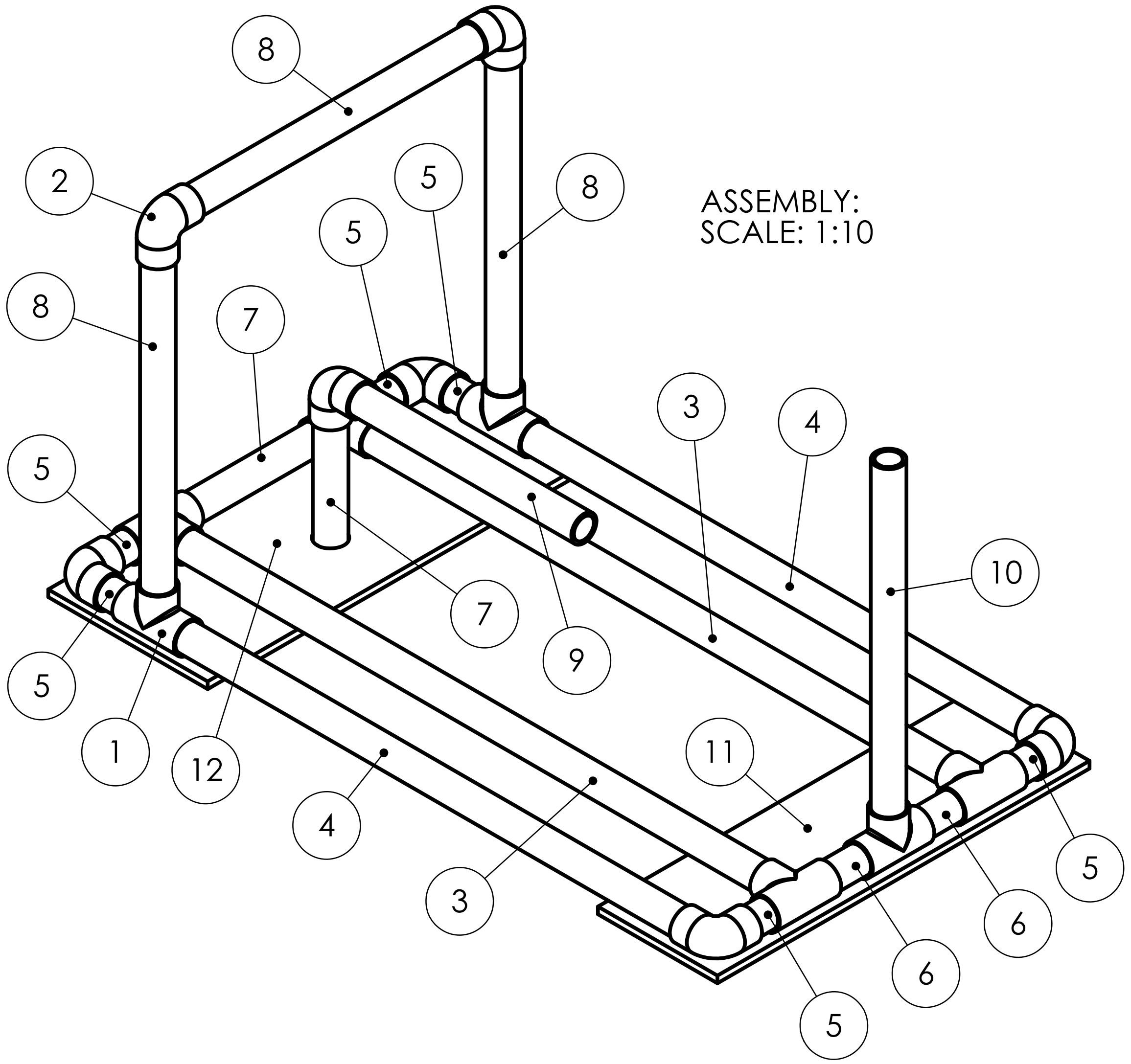
$$\sigma_E = \frac{M_E c}{I} = \frac{(2610 lbft)(1.9")}{4(\frac{\pi}{64}(1.9"^4 - 1.5"^4))} = 3060 psi$$

$$n_s = \frac{S_y}{\sigma_E} = \frac{7000}{3060} = 2.3 > n_d = 2.0$$

Factor of Safety

Lowest $\boxed{n_s = 2.3}$

With wood to support and distribute the load, the actual safety factor will be higher



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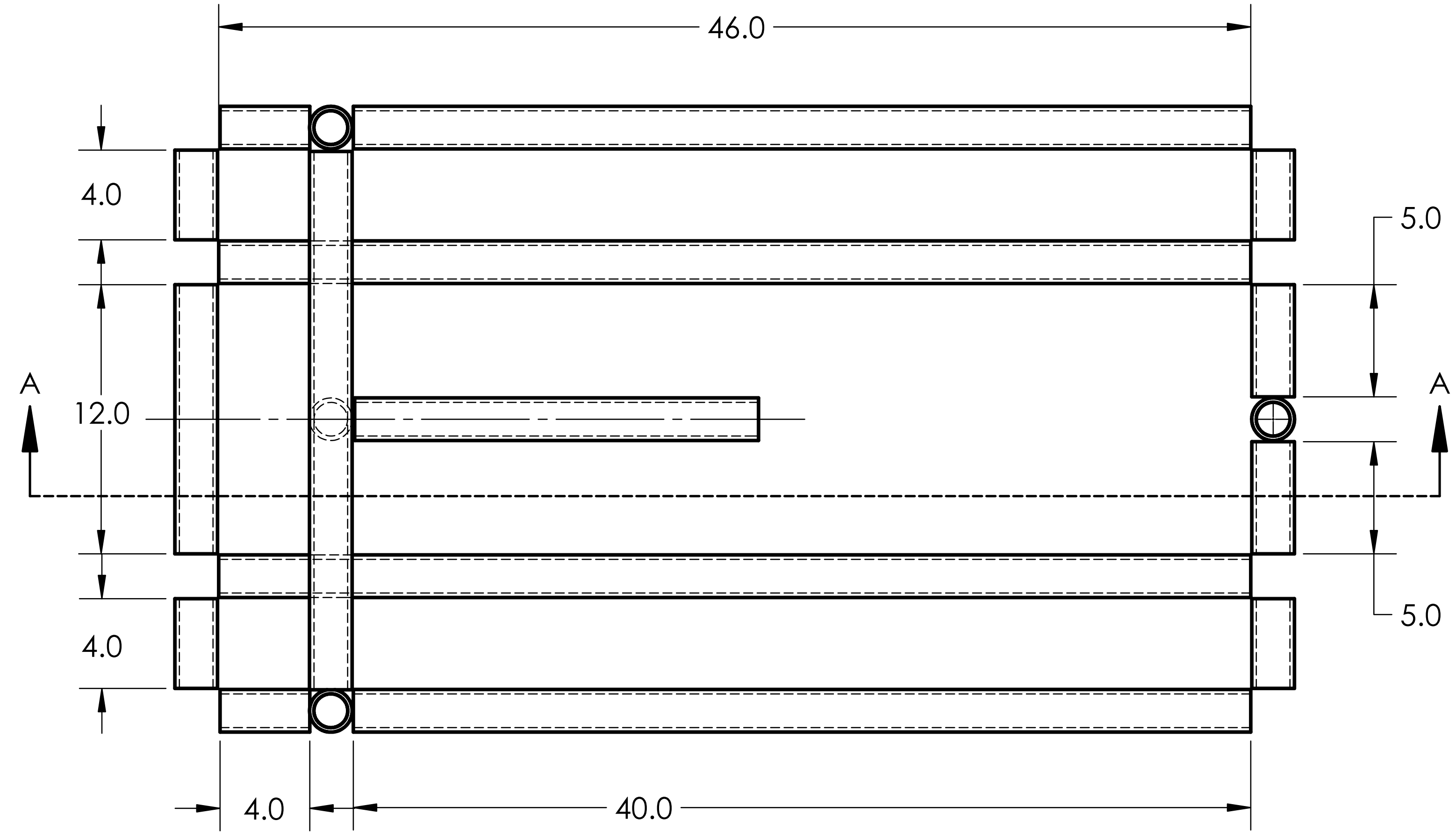
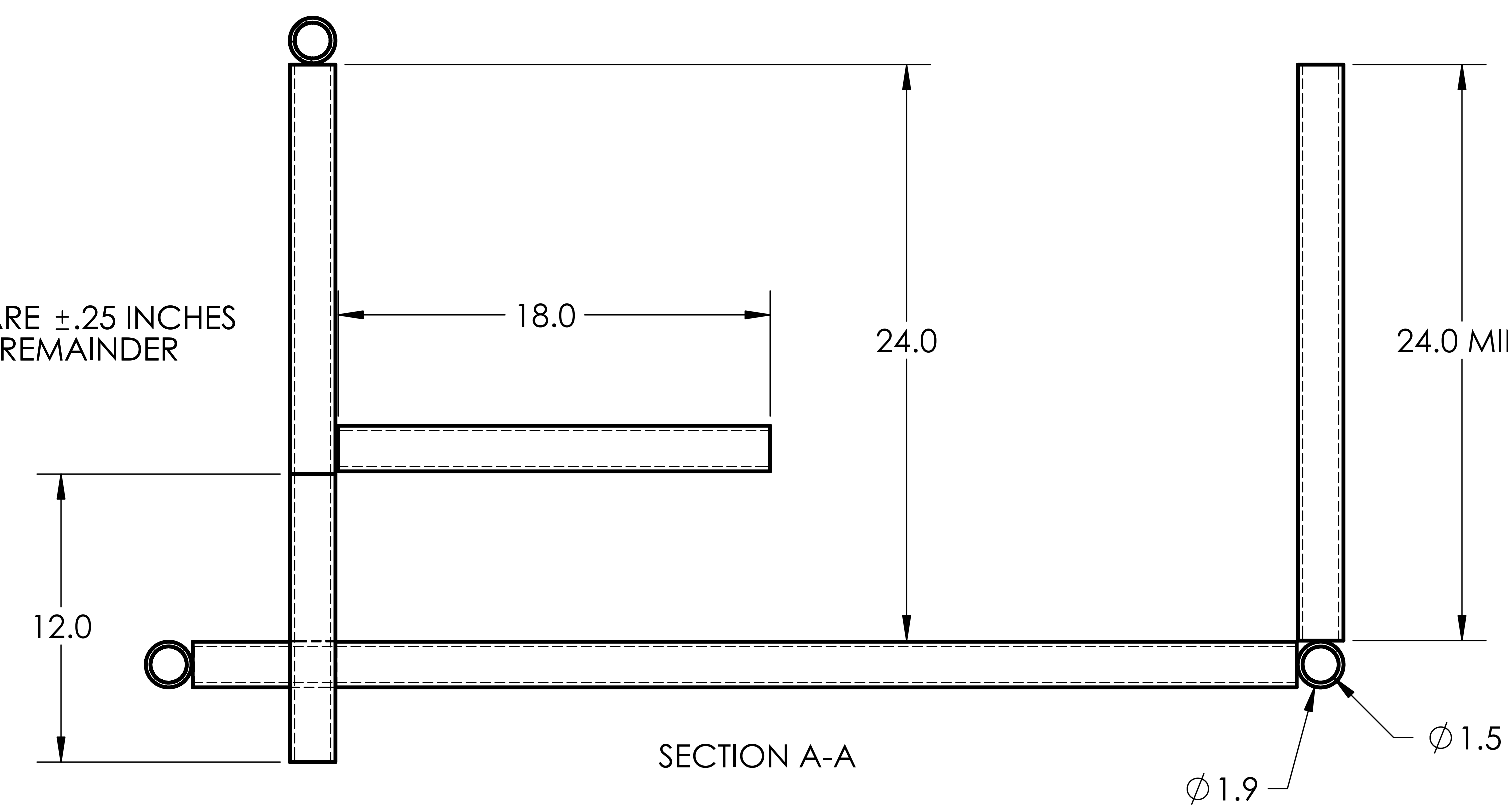




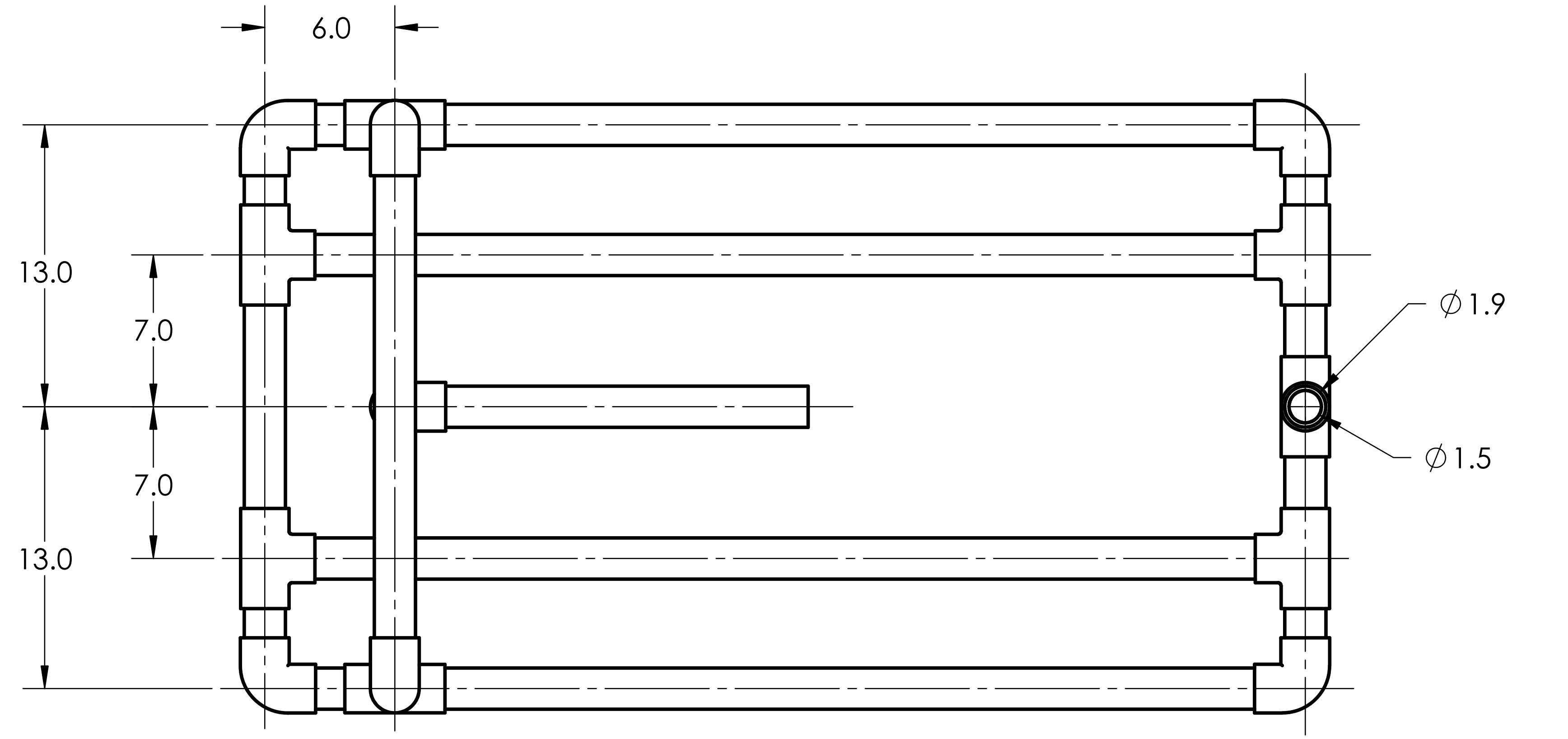
SECTION A-A

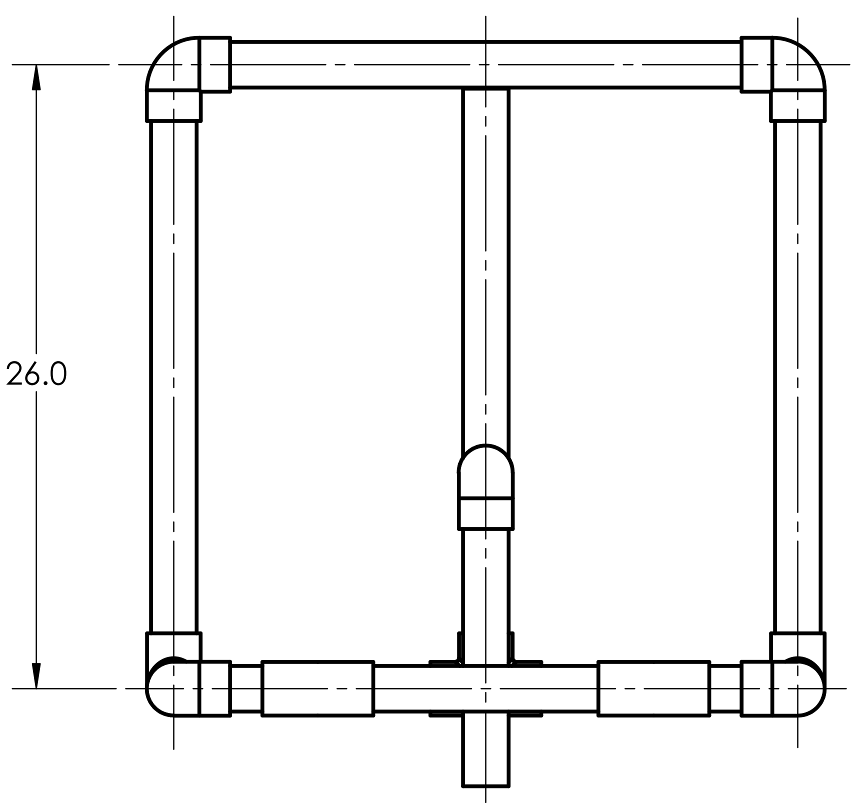
ITEM NO.	DESCRIPTION	QTY.
1	1.5" PVC TEE FITTING	7
2	1.5" PVC CORNER FITTING	7
3	46" PVC PIPE 1.5" ID	2
4	40" PVC PIPE 1.5" ID	2
5	4" PVC PIPE 1.5" ID	6
6	5" PVC PIPE 1.5" ID	2
7	12" PVC PIPE 1.5" ID	2
8	24" PVC PIPE 1.5" ID	3
9	18" PVC PIPE 1.5" ID	1
10	Any Remaining PVC PIPE 1.5" ID	1
11	Front Wood Piece	1
12	Back Wood Piece	1

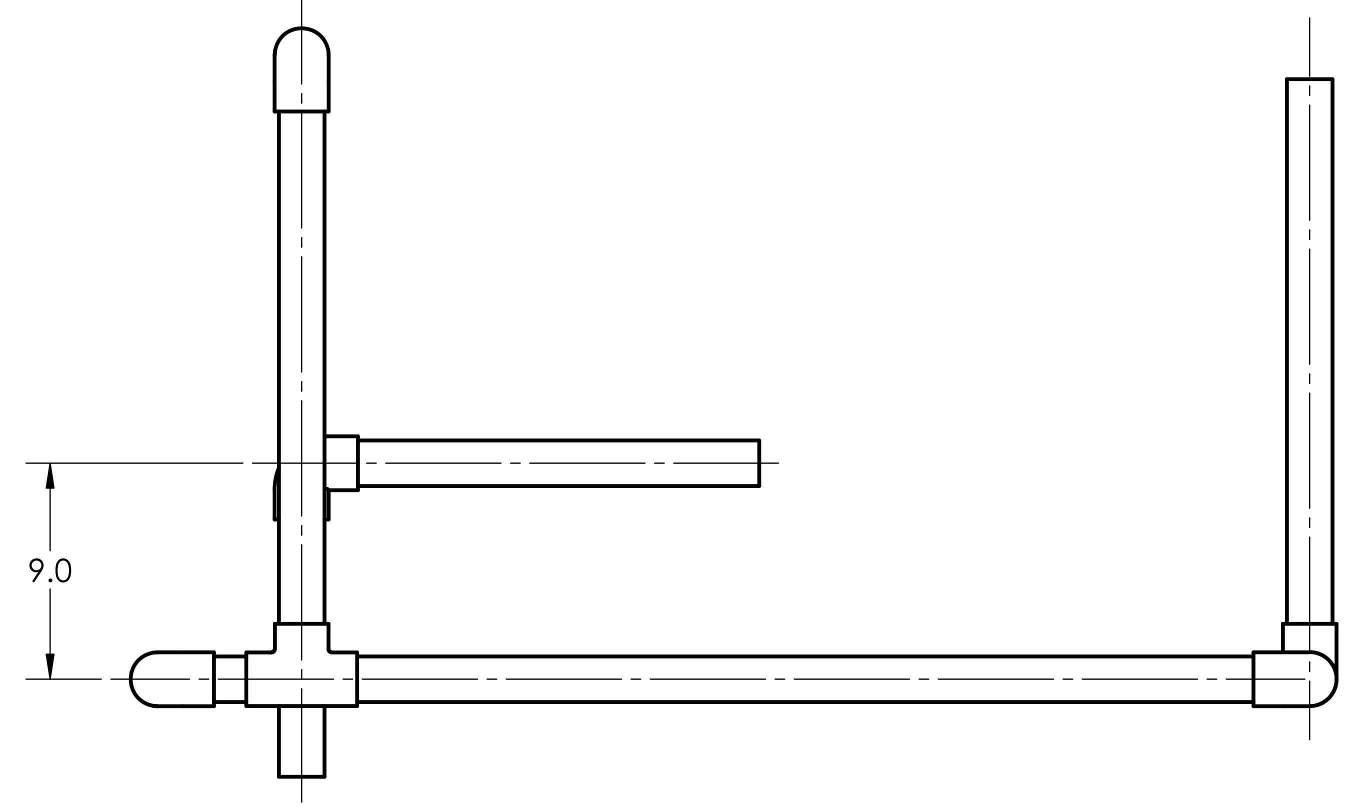
NOTE:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. ALL LENGTH TOLERANCES ARE ±.25 INCHES
3. ITEM 10 LENGTH BASED ON REMAINDER

Cal Poly Mechanical Engineering	Lab Section: 10	Title: FINAL REPORT ASSEMBLY DRAWING		Drwn. By: GARRETT KUNKLER
ME 328 - WINTER 2024	Dwg. #: 1	Date: 3/13/2023	Scale: 1:8	Chkd. By: THE PIRATE'S POSSE

NOTE:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. ALL LENGTH TOLERANCES ARE ±.5 INCHES







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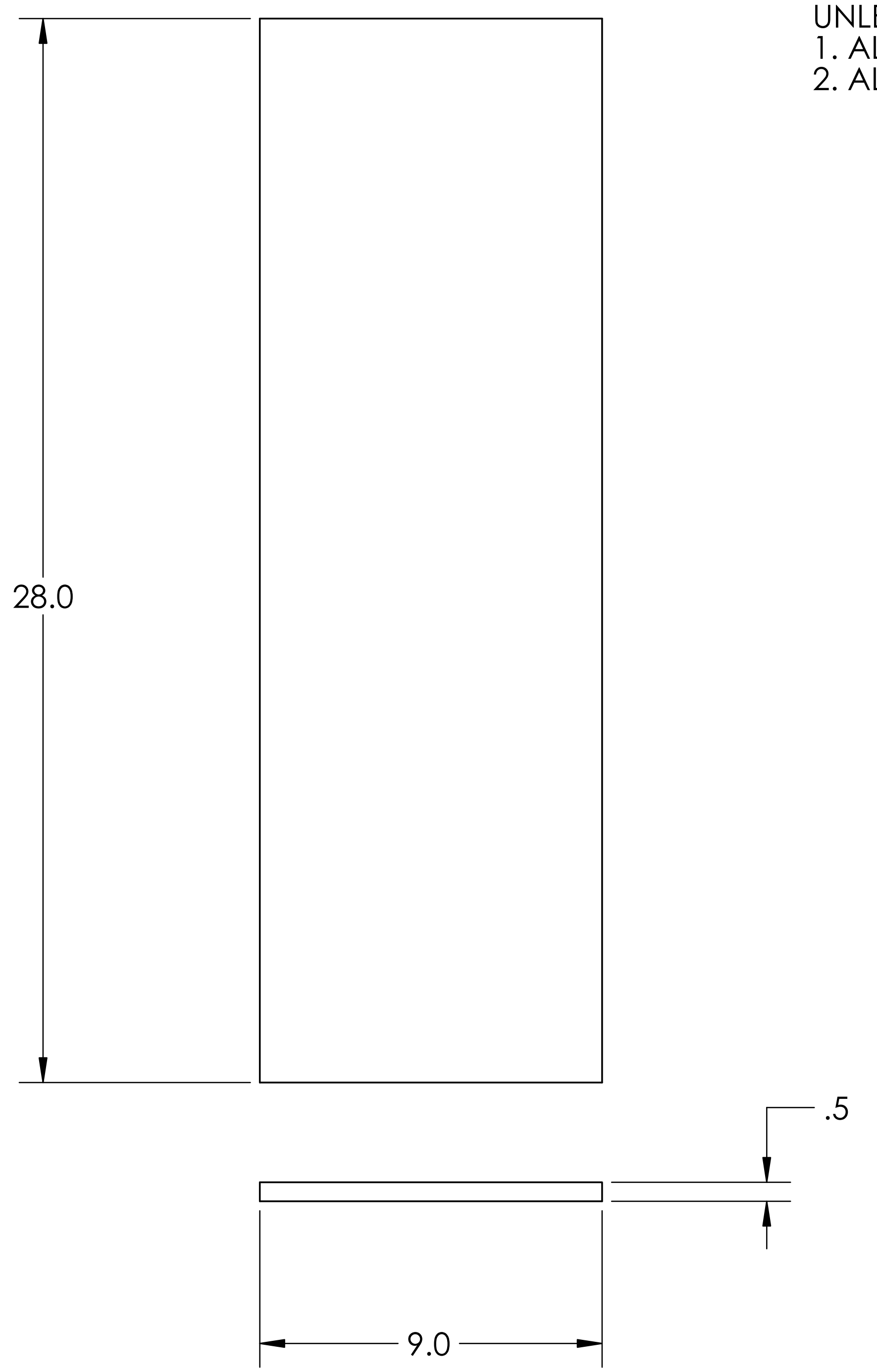
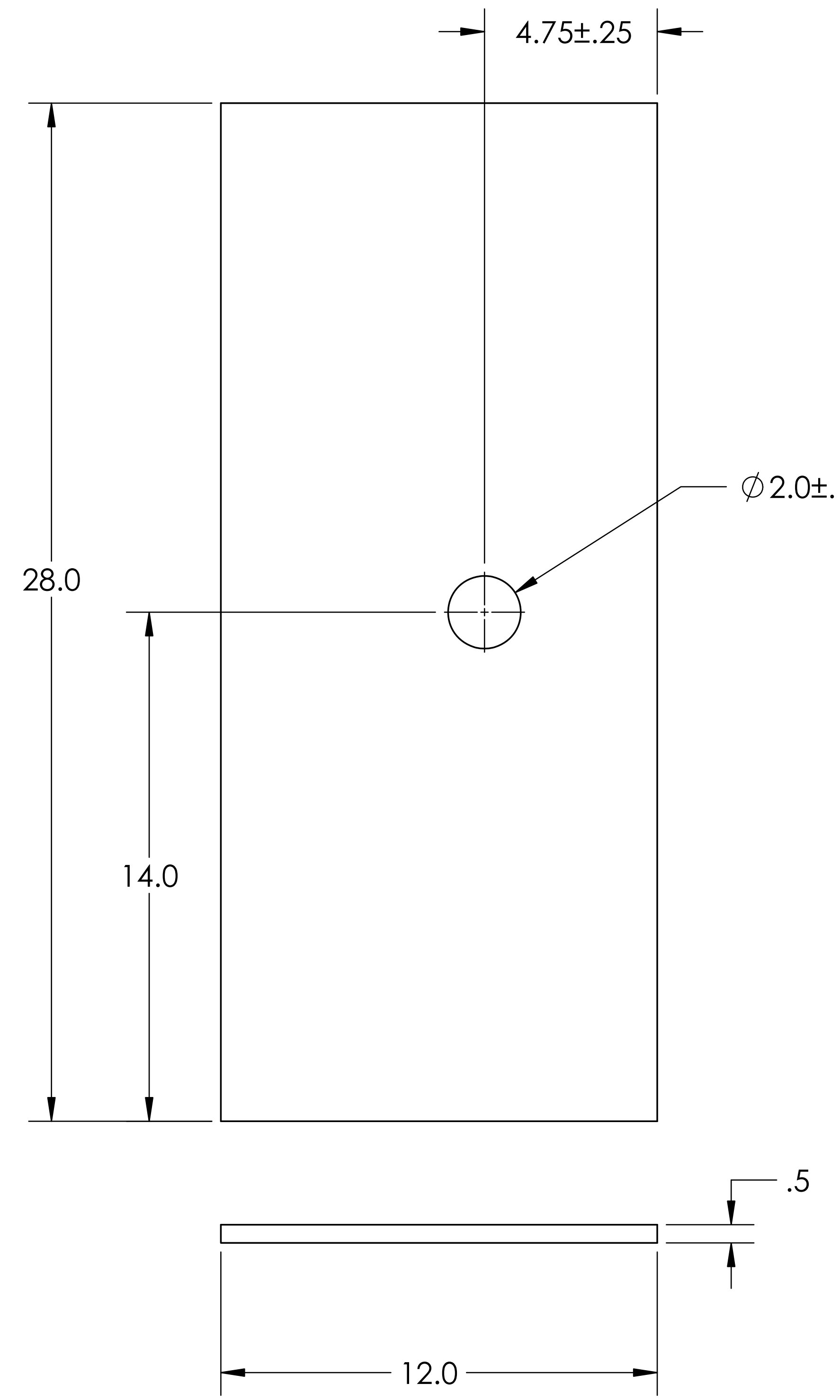
ME 328 - WINTER 2024	Dwg. #: 2	Date: 3/13/2023	Scale: 1:8	Chkd. By: THE PIRATE'S POSSE

PART 11: FRONT WOOD PIECE



NOTE
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES ARE ±.5 INCHES

PART 12: BACK WOOD PIECE



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ME 328 - WINTER 2024	Dwg. #: 3	Date: 3/13/2023 — Scale: 1:5	Chkd. By: THE PIRATE'S POSSE