Ping Pong Ball Launcher

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Introduction

In TAM 212, we focus on the motion of objects. Through this ping-pong project, we are applying theories learned in class to a simple object (ping-pong ball) being launched. We can use theoretical calculations to describe the object's trajectory, but must account for real-world variables to better design a launcher to achieve our target. One variable, drag, must be understood to effectively design our launcher. The effects of drag on an object in motion will experimentally differ, but will affect the capability of hitting a target consistently and thus, must be accounted for in the calculations for design. Through this investigation, we will be able to fully analyze the motion of the ping pong ball to create an optimized ping-pong launcher design. This project is applicable to the real world.

Theory

When you drop an object in air, starting at rest from a sufficiently high height, it reaches a free-fall constant velocity, with an acceleration of zero. At this point, there are two forces acting on the object: gravity and drag. The sum of forces equals zero because acceleration is zero. The free body diagram below shows the acting forces.

The following assumptions were made for simplification: It was assumed that we dropped the object from a sufficiently great height to reach terminal velocity. Additionally, we assumed that the force of drag acting on the object was constant. Natural constants were not measured -- including acceleration of gravity, and density of air.

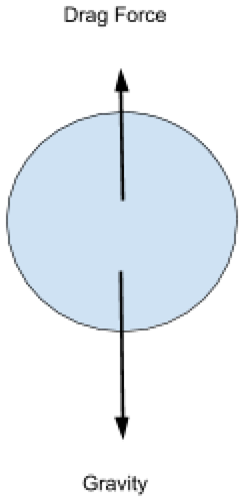

Figure 1: Free body diagram of falling ping pong ball

Force drag, $F_D = cv^2$ where c is the coefficient of drag, and v is the velocity of the object. To solve for c, we can rewrite the equation to be

$$c = -F_D/v^2$$

Knowing that the sum of forces is zero because there is no acceleration at terminal velocity,

$$\sum F_y = F_D - F_g = 0$$

$$F_D = F_g$$

Thus, since the force of gravity $F_g = mg$, we can plug into our earlier equation

$$c = -F_D/v^2$$

To get

$$c = m * g/v^2$$

This calculated drag parameter can be plugged into the equation for theoretical drag coefficient,

$$C_D = \frac{F_D}{\frac{1}{8}\pi\rho D^2 v^2} \text{ to get}$$

$$C_D = \frac{c}{\frac{1}{8}\pi\rho D^2}$$

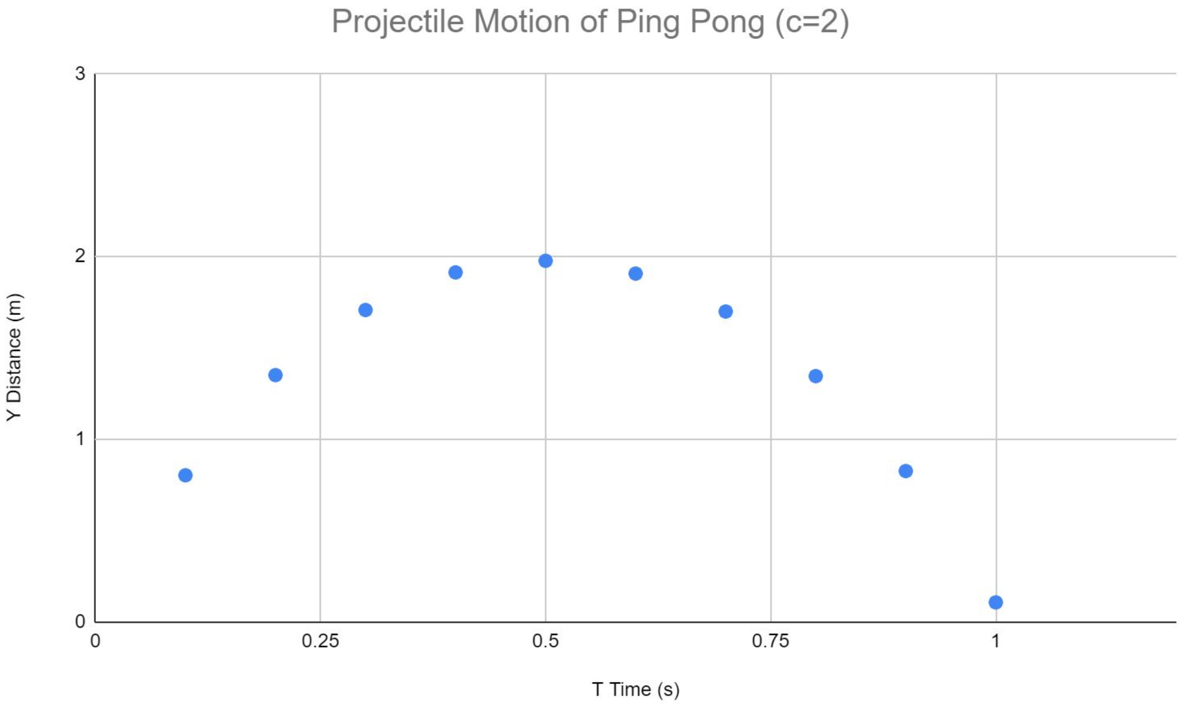

Figure 2: Trajectory plot for a drag parameter of 2

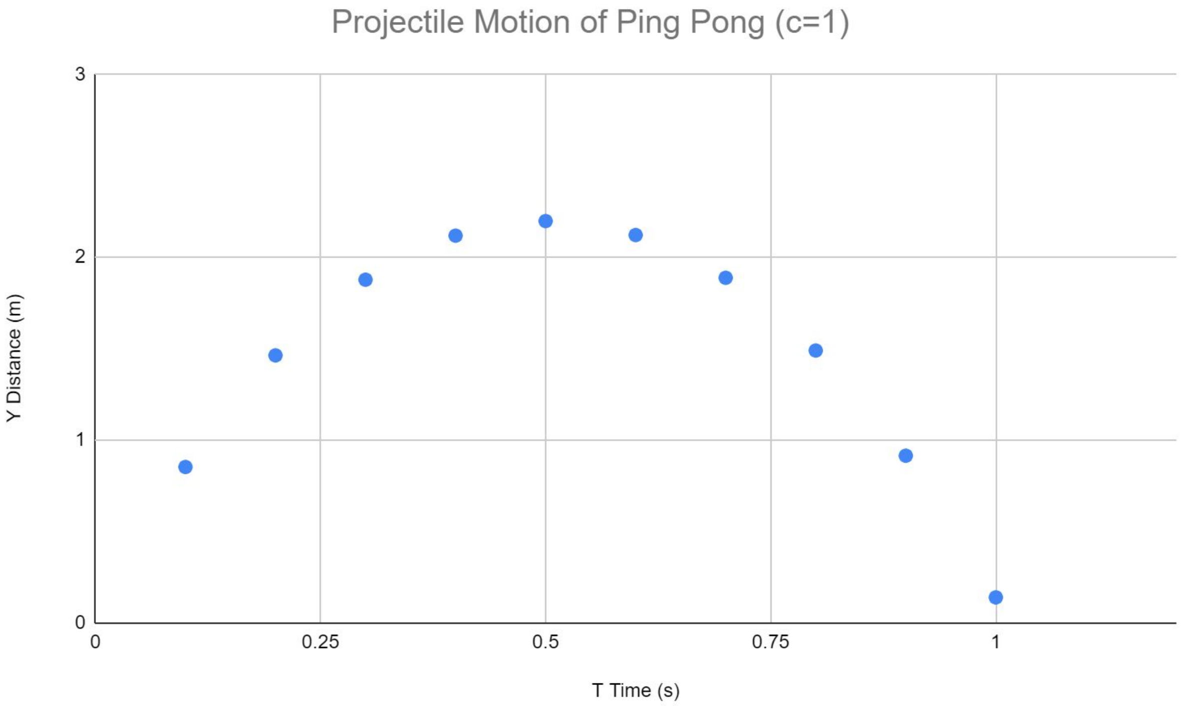

Figure 3: Trajectory plot for a drag parameter of 1

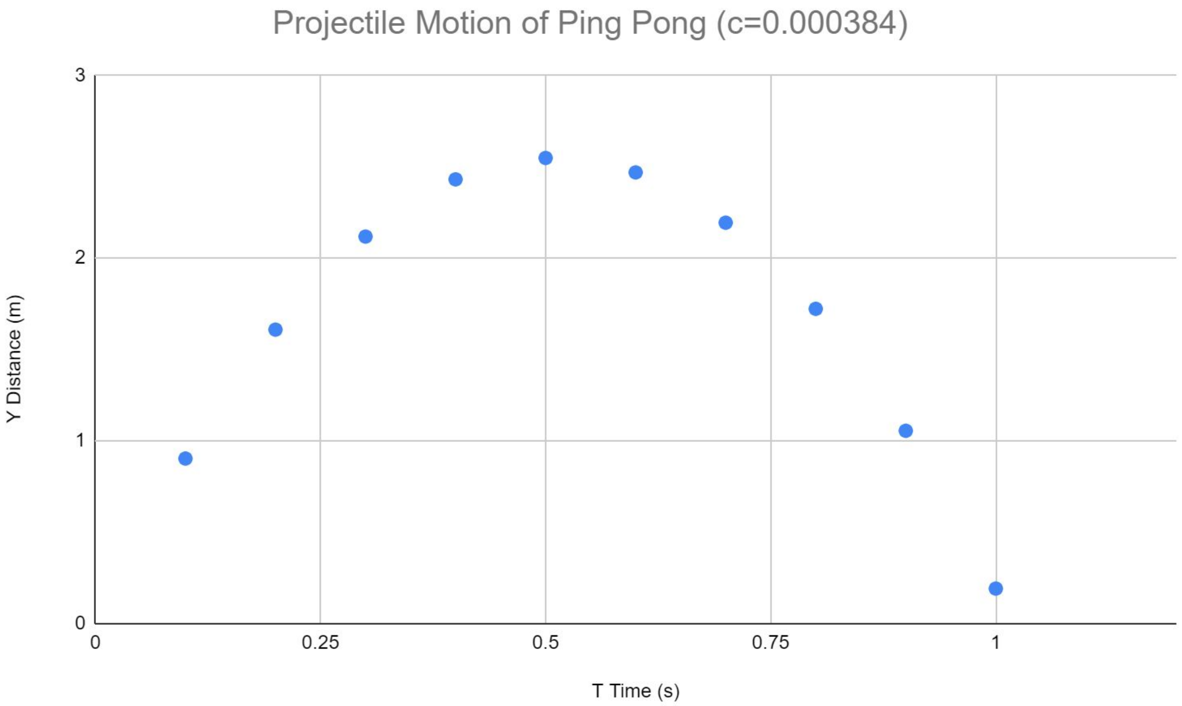

Figure 4: Trajectory plot for theoretical drag parameter of air

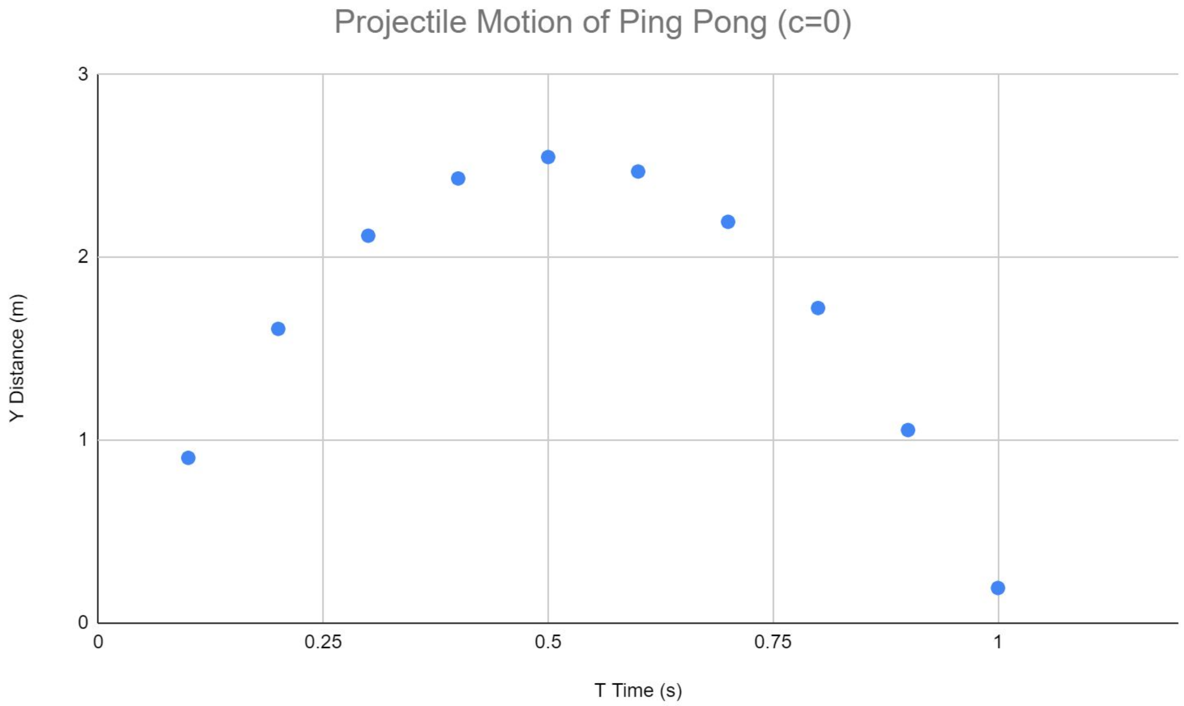

Figure 5: Trajectory plot with no drag

Based on our above plots, as the drag parameter decreases the ping pong ball obtains a more parabolic trajectory, reaching a higher max height.

Experiment Design & Results

Materials

- Ping pong ball
- Ruler / meter stick
- Stopwatch / timer
- Weighing scale
- Digital camera
- Video analysis software

Process

From the equations above, we know that we need the mass of the object, and the velocity at which it travels.

1. Record the mass and diameter of the ping pong ball.
   Mass: 2.772 g , 2.773g, 2.770g, 2.770g, 2.770g
   Diameter: 0.04 m

2. Using the theoretical coefficient of drag, calculate the height from which the ping pong ball will reach terminal velocity, and increase it.
3. Set up the camera, and a meter stick and stopwatch within the camera frame.
4. Start the camera and then stopwatch. From a previously calculated estimated height, drop the ping pong ball into the frame.
5. Use a video analysis software (like Tracker) to follow the motion of the ping pong ball and find its velocity in the y-direction as it falls. Analyze the different points to determine when the ping pong ball reaches terminal velocity, where the velocity is constant. This velocity will be used to find the coefficient of drag.
6. Repeat steps 3-5 until sufficient data has been gathered.

Results: Drag Parameter

Velocity (m/s)	***Drag Parameters (kg/m)***
8.641	$3.641 * 10^{-4}$
8.729	$3.568 * 10^{-4}$
8.229	$4.014 * 10^{-4}$
7.848	$4.414 * 10^{-4}$

Figure 6: Table of terminal velocities and their corresponding drag parameters

We calculated the drag parameter values using the velocity values above and the equation $c = m * g/v^2$.

Parameter	***Value***
Sample Size	4
Mean	$3.909 * 10^{-4}$ kg/m
Std Dev	$3.891 * 10^{-5}$
Theoretical	$3.848 * 10^{-4}$ kg/m

Figure 7: Table containing statistics and and theoretical value for drag parameter

From our experimental data, we estimated that the drag parameter c for our ping pong ball is approximately $3.909 * 10^{-4}$ kg/m (the calculated average). This experimental constant turned out to be 1.57% larger than the calculated theoretical value.

Results: Drag Coefficient

$$F_d = m * g$$
$$F_d = \; -cv^2$$
$$c = F/v^2$$
$$C_D = \frac{c}{\frac{1}{8}\pi\rho D^2} = 0.508$$

Parameter	***Value***
Sample Size	4
Mean	0.508
Std Dev	0.051
Theoretical	0.500

Figure 8: Table containing statistics and theoretical value for drag coefficient

Our estimation for C_d was 0.508. We calculated the drag coefficient using the equation found above, taking the c values from the previous part. This was 1.57% larger than theoretical. It makes sense that the percent error is identical to c, because C_d should scale linearly with any errors in c.

Results: Reynolds Number

$$\rho = 1.225 \text{ [kg/m^3]}$$
$$v = \; 8.36 \; \text{[m/s]}$$
$$\mu = 18.6 * 10^{-6} \; \text{[Pa*s]}$$
$$\mathrm{D} = 0.04 \text{ [m]}$$
$$Re_d = \frac{\rho v D}{\mu} = 22{,}023$$

This high Reynolds number indicates that the flow around the ping pong ball is turbulent, since its value is above 4,000. This seems like a reasonable result in line with our assumptions, as we assume drag force to be the primary force acting on the ping pong ball. If the Reynolds number was low, that would indicate that there are high shear forces acting on the ping pong ball produced by the high viscosity of the fluid. The viscosity of air is very low, and in real life the primary forces are produced by the effects of drag, and thus not expected to have laminar flow, and have a high Reynolds number.

Results: Sources of Error

One potential source of error that we are bound to encounter is the accuracy of our camera and digital analysis software. It's possible that due to our camera, we won't be able to capture the correct point of time when the ping pong reaches its constant velocity. This could possibly be a pretty significant error, depending on how small the error in time is, how much error we encounter due to our camera frame rate, and to what precision we need it to be.

Another source of error could come from the measurement of the mass of ping pong ball. The source of this error likely will not be too significant if we use a fairly high precision balance. There also is the potential for variation in the mass of the ping pong ball if we do not use the same one for every single experiment. This error likely will be minimal.

Additional error can arise from air drafts/breeze causing inconsistent drag on the ball. This can be minimized by performing the experiment indoors in a location away from drafts, and is likely insignificant, and can be accounted for by doing multiple trials.

Launching Mechanism

Launching Mechanism Design

Our launcher mechanism utilizes an internal pin-projection mechanism with capabilities to adjust launch speed and projectile angle. Siemens NX 12.0 was used for CAD design of the main components of the launcher including the ping pong holder, main shaft, internal pin, and base mounting. All other parts (bolts, cardboard, rubber bands, etc.) can be found in the *Materials* section below. The *CAD* section details how the launching mechanism functions.

Materials

Part Name	***Additional Details***	***Quantity***
Ping Pong Holder	3D printed	1 part
Main Shaft	3D printed	1 part
Internal Pin	3D printed	1 part
Base Mounting	3D printed	1 part
Threaded Bolt	M6 x 7.5mm	1 part
Nut	M6	1 part
Washers	M6	1-2 parts
Nail	1.5 in. x 12 gauge	1 part

Rubber Bands	Add incrementally (x2) for increased strength	2-4 parts
Super Glue	Loctite Super Glue, Liquid	1 bottle
Cardboard	Multiple sheets for increased base strength,Dimensions at least 1 ft x 1ft (dimension not critical)	3-4 sheets
Protractor	For angle measurement	1 tool
Ping Pong Ball	Standard size	1 ball

CAD

The following images detail the CAD design for each of the 3D printed parts.

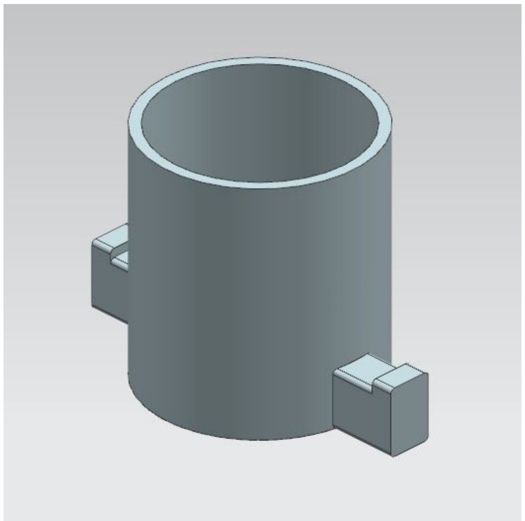

Figure 9: Ping Pong Holder

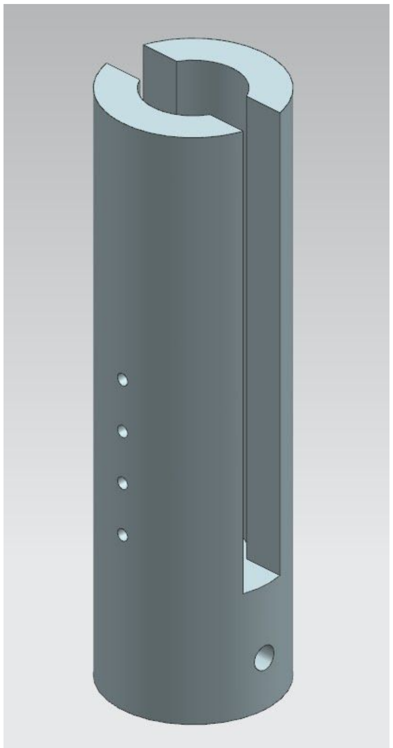

Figure 10: Main Shaft

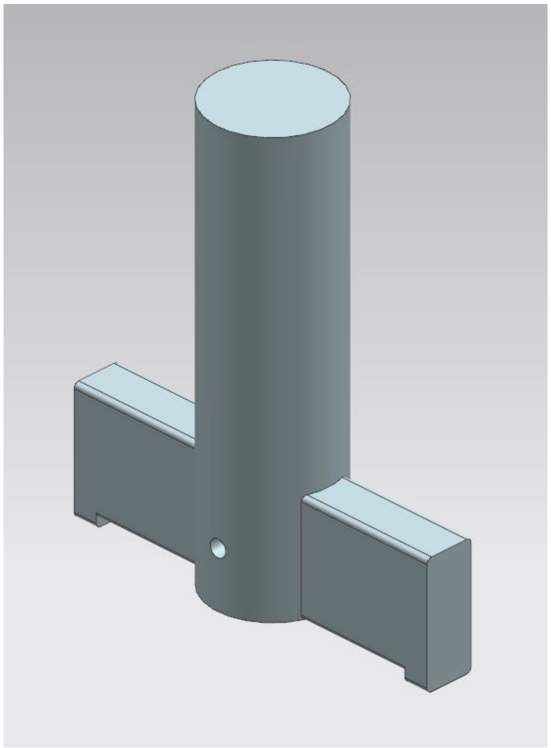

Figure 11: Internal Pin

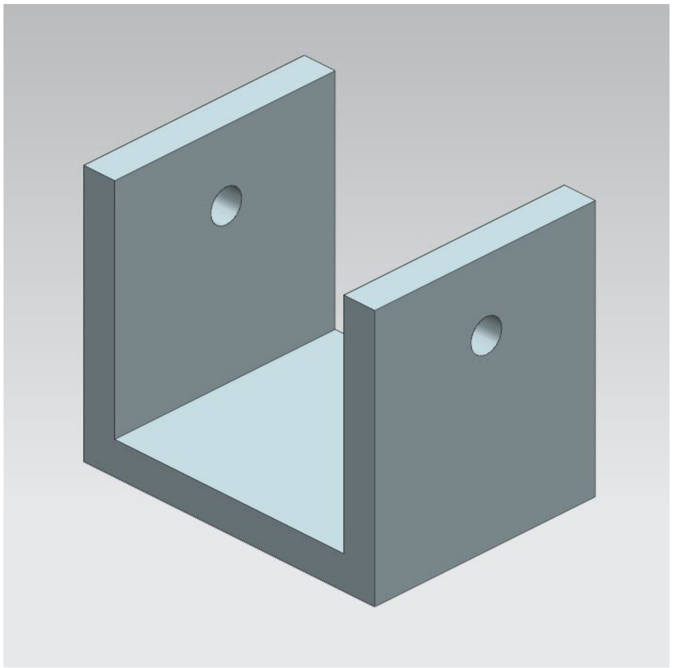

Figure 12: Base Mounting

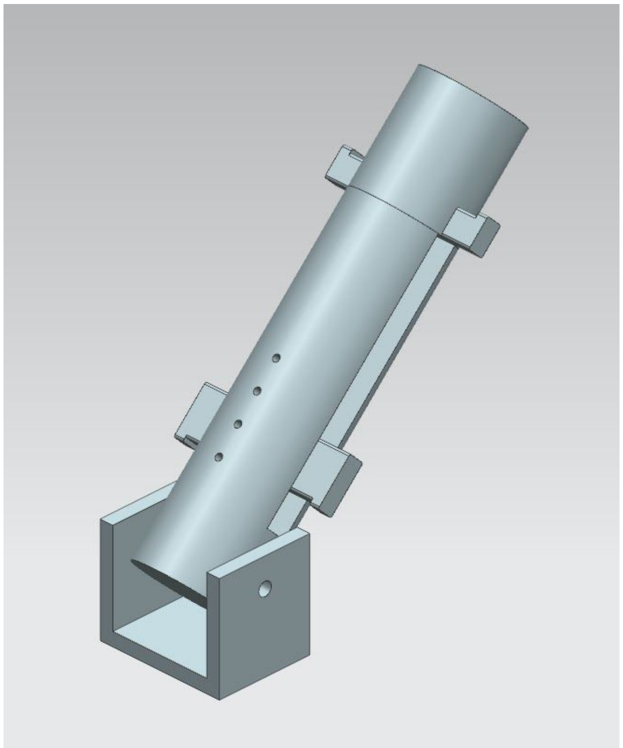

Figure 13: Final CAD Assembly (Isometric)

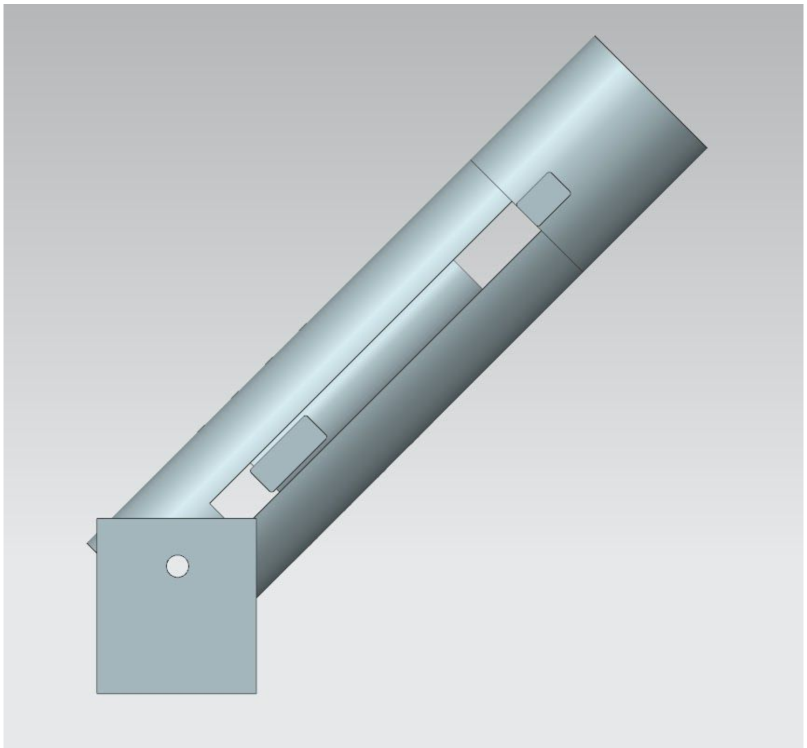

Figure 14: Final CAD Assembly (Side View)

Construction

The following steps detail how this launcher's total assembly was completed:

1. 3D print the .stl CAD files for the "ping pong holder," "main shaft," "internal pin," and "base mounting."
2. Assemble the main launching parts with the "ping pong holder," "main shaft," and "internal pin."
   a. Place the "main shaft" upright
   b. Slide the "internal pin" into its slot with widest the portion of the part sliding in first.
   c. Glue the "ping pong holder" to the top of the "main shaft" with super glue. Ensure that the tabs on the "ping pong holder" match the orientation of the "internal pin."
3. Take a few sheets of cardboard and trim down to size. Dimensions of the cardboard base are not critical. At least a 1 ft by 1 ft base is recommended for stability.
   a. Stack and glue the pieces of cardboard together for increased stiffness and stability.
4. Take the "base mounting" 3D printed part and glue the bottom to the cardboard. Exact placement of the piece is not critical, but close to the center is recommended.
5. Once the glue of the base has dried, attach the main launching sub-assembly (step 2) to the "base mounting" part with the bolt, nut, and washers.
6. To attach rubber bands, stretch a rubber band around each side of the pegs. Add more rubber bands to increase initial velocity.
7. To control the consistency of the launch, slide the nail through the "main shaft" and "internal pin" at the desired launch configuration. Remove the nail to launch.

8. Refer to images shown in ***Fabricated Launching Mechanism*** for assistance in assembly.

Fabricated Launching Mechanism

See the following video for the launcher being used in action: https://drive.google.com/file/d/1Ri3KvrUuibCPuzR8ARQXHg4c03c_a0Rc/view?usp=sharing

Figure 15: Front view of launching mechanism

Figure 16: Back view of launching mechanism

How to Launch

To launch a ping pong ball…

1. Place the desired number of rubber bands on each side of the launcher pegs.
2. Pull the internal pin back until it is at its desired location.
3. Place a nail through the main shaft and internal pin to hold in place.
4. Adjust the launcher to the desired angle (use a protractor if necessary).
    a. Secure the bolt with the nut to lock the angle in place. If more support is needed, place an additional cardboard support under the main shaft.
5. To release the pin, simply remove the nail holding the pin in place.

How to Control Velocity

There are two ways in which the velocity can be controlled with this mechanism:

1. Pulling the "internal pin" back further within the "main shaft." Lock in place with the nail until launch is desired.
2. Adding more rubber bands to either side of the pegs.

Conclusion

In our ping pong ball report we first designed and conducted an experiment to obtain values of the drag parameter and drag coefficient. Through this experiment, we found that our experimental value of drag for a ping pong ball was very similar to the theoretical value.

Therefore, we can conclude that the theoretical model of drag for a ping pong ball is quite accurate. Additionally, we were also able to calculate the Reynolds number, which is used to distinguish different types of flow. Since we had a high Reynolds number, we determined that the air flow around a falling ping pong ball is turbulent. Based on these results, we found that it is necessary to account for air resistance if the ball is travelling a long distance. This is because drag over a long period of time affects the ball significantly enough that it will miss its target.