# TAM 212 Group Project:
# Ping Pong Ball Launcher

University of Illinois at Urbana-Champaign

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Figure 1: Not a ping pong ball launcher.

# Ping Pong Ball Launcher

## 1 Learning Objectives

This project is not a typical assignment. It is not a textbook problem, which only has one correct answer and typically takes a few hours at most to complete. Nor is it a laboratory experiment, which only requires data collection and reduction, and in which each step of the procedure is given in detail. While both of those types of assignments are useful, they are not very realistic. Real-world problems rarely have a single, correct answer, and scientists and engineers are never told how to solve them: they have to figure that out for themselves.

This project is designed to help you develop skills you will need if you go on to become a professional engineer or scientific researcher. These skills include, but are not limited to,

- working collaboratively as part of a team
- applying critical thinking skills to open-ended, real-world problems
- identifying assumptions you make when analyzing a problem
- assessing the validity of your assumptions
- solving differential equations numerically (e.g., with Microsoft Excel®)
- designing and performing your own experiments
- collecting data using commonly available devices
- comparing experimental results to theoretical predictions
- identifying sources of error in an experiment
- assessing the validity of a theoretical model
- fabricating a device to consistently achieve a practical goal

To that end, this project is extremely open-ended. There are multiple ways to do it, and you are free to approach it however you like—though you should be aware that some ways are better than others. In keeping with this freedom, you will be given an extensive amount of time to complete the project, and minimal guidance along the way. If at any time you feel that the instructions are vague, or that you are not given enough information, do not be alarmed: that is by design! The point is for you to figure out as much as possible on your own. If you need assistance, you are encouraged to consult one of the many references available to you (the internet is a great, if sometimes inaccurate, source of information, and anything you cannot find on the internet can be found at Grainger Library). You should also feel free to ask the instructors for assistance. At the end of the day, though, the project belongs to you: you are responsible for the quality of your finished product. Do well, and have fun!

# 2 Problem

Consider a ping pong ball moving through the air. The motion of an object though a fluid is one of the most complex problems in all of science, and it is still not completely understood to this day. One of the reasons this problem is so challenging is that, in general, there are many different forces acting on such objects, including gravity, drag, lift, thrust, buoyancy, bulk fluid motion (such as wind), and inertial forces (such as the centrifugal and Coriolis forces). In most introductory physics and dynamics courses, gravity is the only force that is accounted for. This is equivalent to assuming that the motion takes place in a vacuum and an inertial reference frame. But what about the other forces? In this project, you will investigate the effect of the drag force on a ping pong ball, and you will design a launching mechanism capable of consistently hitting a target in the presence of air resistance.

# 3 Project Tasks

This project has three parts:

1. Projectile Motion Analysis
2. Experimental Drag Parameter Determination
3. Launching Mechanism Design and Fabrication

## Part 1: Projectile Motion Analysis

(a) Derive the equations of motion for a spherical projectile near the surface of the earth in the presence of both gravity and quadratic drag. The drag force vector is given by $\mathbf{F}_D = -cv^2\hat{\mathbf{v}}$, where $c$ is called the *drag parameter* and depends on the size of the projectile, $v$ is the speed of the projectile, and $\hat{\mathbf{v}}$ is the unit vector in the direction of the projectile's velocity.

(b) Think about all of the assumptions and simplifications you made in the process of your derivation—there are many! List as many as you can possibly think of, and discuss how valid each assumption is.

(c) Using Excel®, implement a numerical integration scheme to solve your equations of motion for the general case of coupled horizontal and vertical motion. Include cells for the initial conditions, time step, and all other relevant parameters, including $c$. Plot the trajectory ($y$ vs. $x$) with drag against the parabolic trajectory in a vacuum.

## Part 2: Experimental Drag Parameter Determination

(a) Based on your analysis, design a simple experiment to measure the drag parameter $c$ for a ping pong ball. Do *not* assume that $c$ is equal to its theoretical value of $\pi\rho D^2/16$ for a sphere, where $\rho$ is the density of air and $D$ is the diameter of the sphere. You are free to design any kind of experiment you want, but be aware that some experiments are easier to perform and more accurate than others. The following is a list of resources you may or may not find useful. Many of them are available upon request during office hours.

- ruler / meter stick
- tape measure
- compass
- protractor
- stopwatch / timer
- weighing scale
- force gauge
- rope / string
- digital camera
- video analysis software (available to download for free online)

Disclaimer: Some of the above items may not be accurate enough to yield good results. You are not required to use any of these if you do not want to, and you are absolutely free to use anything not listed here. Part of the project is learning how to take accurate measurements.

(b) Think about all of the sources of error in your experiment. List as many as you can possibly think of. (Do *not* include "human error," though, as that is simply a euphemism for "doing the experiment wrong.") Discuss how significant each source of error is. If possible, revise your experimental design until it has the least possible error.

(c) Conduct the experiment you have designed on a ping pong ball.

(d) From your experimental data, estimate the drag parameter $c$ for your ping pong ball. Report your estimate using appropriate statistics (sample size, mean, and standard deviation). Compare your estimate for $c$ to the theoretical value of $\pi \rho D^2/16$ for a sphere.

(e) The *drag coefficient* for a sphere is defined as $C_D = F_D/(1/8)\pi\rho D^2 v^2$, where $F_D$ is the magnitude of the drag force, and all other quantities are as defined previously. Derive a relationship between $C_D$ and $c$, assuming quadratic drag. Using this relationship and your estimate for $c$, estimate $C_D$ for your experiment. Report your estimate using appropriate statistics (sample size, mean, and standard deviation). Compare your estimate for $C_D$ to the theoretical value of 1/2 for a sphere.

(f) From your experimental data, calculate a Reynolds number that is representative of your experiment. Is your Reynolds number consistent with your assumptions?

NOTE: If you are not happy with your results, you are free to repeat your experiment as many times as you wish before the due date. That is one of the reasons you are given so much time.

### Part 3: Launching Mechanism Design and Fabrication

(a) Design a ping pong ball launching mechanism capable of consistently hitting a target an arbitrary distance $L$ away from the launcher and an arbitrary height $H$ above the ground (see Figure 2). Again, you are free to design any kind of mechanism you want, though you must be able to construct it using materials available to you. We recommend something simple (hint: rubber bands are good). NOTE: During the last Discussion, you will be given a target with specific values of $L$ and $H$, which you will need to hit a certain number of times in order to receive full credit for the project.

(b) Fabricate the ping pong ball launcher you have designed.

(c) Construct a simple physical model of your ping pong ball launcher that allows you to accurately predict and control the launch velocity of the ping pong ball.

## 4 Timeline and Deliverables

To keep you on track, there will be various checkpoints throughout the semester, when specific parts of the project are due. These checkpoints are summarized in Table 1.

Table 1: Checkpoints and corresponding deliverables.

| **Checkpoint** | **Parts to be Completed** | **Deliverables** | **Point Value** |
|---|---|---|---|
| Discussion Oct 5-6 | Part 1 | Working Excel® spreadsheet<br>(to be completed during Discussion) | 0 |
| Discussion Oct 26-27 | Part 2 (a),(b) | Description of experimental design and data to be taken<br>(to be turned in at the beginning of Discussion) | 5 |
| Discussion Nov 2-3 | Part 2 (c) | Preliminary experimental data<br>(to be shown to TA's at the beginning of Discussion) | 5 |
| Discussion Nov 9-10 | Part 2 (d),(e),(f) | Estimates for $c$ and $C_D$, with statistics<br>(to be turned in at the beginning of Discussion) | 5 |
| W Nov 15 | Part 3 | Draft of report (in Compass) | 5 |
| W Nov 29 | | Peer review feedback (in Compass) | 5 |
| Discussion Nov 30 - Dec 1 | | Peer review feedback (in Discussion) | 5 |
| W Dec 6 | | FINAL REPORT (in Compass)<br>Final Excel® spreadsheet (in Compass) | 55<br>5 |
| Discussion Dec 7-8 | | Launching mechanism contest<br>(to be decided during Discussion) | 10 |

## 4.1 The Excel® Spreadsheet

Each group will construct the Excel® spreadsheet for Part 1 (c) during one of the Discussion worksheets, as indicated in Table 1.

## 4.2 Experimental Design

Each group should design its experiment outside of class. A detailed description of the experimental design, and the data to be taken, must be turned in at the beginning of the Discussion period indicated in Table 1.

## 4.3 Experimental Data

Each group should perform its experiment outside of class as well. Preliminary experimental data is due at the beginning of the Discussion period indicated in Table 1. For this check-point, you do not need to turn anything in; you simply need to show your TA the data your group has taken (e.g., on your computer).

## 4.4 Estimates for $c$ and $C_D$

Each group should report its estimates for $c$ and $C_D$ using appropriate statistics (namely, sample size, mean, and standard deviation). Your sample size is the number of times you performed your experiment. The mean and standard deviation for $c$ can be computed using Excel®. The mean and standard deviation for $C_D$ can be computed from the mean and standard deviation for $c$ using the relationship you derived in Part 2 (e). These estimates are due at the beginning of the Discussion period indicated in Table 1.

## 4.5 The Report

Each group must present its work in a formal, written report. At minimum, the report should contain the following sections:

- Introduction
- Theory
- Experiment Design & Results
- Discussion of the Results
- Launching Mechanism
- Conclusion

You are free to add additional sections or subsections as you see fit. There is no page limit on the report; it should be as long as it needs to be in order to convey all the necessary information, and no longer. Write your report so that an educated reader who is unfamiliar with the material could follow and reproduce everything you have done. For more details about what to include in each section, and its approximate point value, see Table 2.

Table 2: What to include in the report.

| Section | What to include | Point Value |
|---|---|---|
| Introduction | -The motivation behind the project, as you understand it | 2 |
| | -A description of what you will achieve by the end of the report | 3 |
| Theory | -A detailed discussion of all the assumptions you made in your analysis | 2 |
| | -A detailed derivation of all the equations you will use in the report, including the equations of motion and the numerical integration scheme | 3 |
| | -A plot of various trajectories obtained from your Excel® spreadsheet with different values of $c$, illustrating motion with and without quadratic drag | 2 |
| Experiment Design & Results | -A step-by-step procedure for your experiment, with enough details that the reader could reproduce what you did exactly | 2 |
| | -The mass and diameter of your ball | 2 |
| | -A representative Reynolds number for your experiment, with enough details that the reader could reproduce it exactly | 2 |
| | -The data you obtained, in tabular and/or graphical form (use your judgment) | 5 |
| | -Your estimate for $c$ (sample size, mean, and standard deviation) | 3 |
| | -A description of how you obtained your estimate for $c$ from your data, with enough details that the reader could reproduce your estimate exactly | 3 |
| | -Your estimate for $C_D$ (sample size, mean, and standard deviation) | 3 |
| | -A description of how you calculated your estimate for $C_D$ from $c$, with enough details that the reader could reproduce your estimate exactly | 3 |
| Discussion of the Results | -A comparison between your estimate for $c$ and its theoretical value | 2 |
| | -A comparison between your estimate for $C_D$ and its theoretical value | 2 |
| | -A detailed discussion of all the sources of error in your experiment, whether the sources of error you identified can account for the differences between the theory and your results, and how your experiment could be improved | 3 |
| Launching Mechanism | -A detailed description of the launching mechanism you designed, with enough details that the reader could reproduce it exactly | 3 |
| | -Detailed photos of the launching mechanism you fabricated | 2 |
| | -A detailed description of your physical model for the launching mechanism, and how you can use it to control the launch velocity of the ping pong ball | 3 |
| Conclusion | -A concise summary of your entire report thus far | 1 |
| | -Answers to the following questions, along with sufficient justification: | |
| | 1. How accurate is the theoretical model of drag for a ping pong ball? | 2 |
| | 2. Is it necessary to account for air resistance in order to hit a target with a ping pong ball? | 2 |

### 4.5.1 Report submission procedure

*Draft*: A draft of your report is due by the date indicated in Table 1. *Each member of the group* should submit (i) your draft in PDF format and (ii) your Excel® spreadsheet in Compass by that date.

*Peer Review and Feedback*: Once the deadline for the first draft has passed, Compass will assign each student two submissions to review. You should grade each of the submissions you are assigned out of 60 points (the report is worth 55 points, according to the rubric in Table 2, and the spreadsheet is worth 5 points). Take off 1 point for each missing or incorrect unit in each section, up to the total number of points for that section. Note that this score is only meant to give the group an idea of what they need to do for the final draft; it will not actually affect their project grade. You should also provide relevant comments and suggestions within the appropriate field. Your feedback will be graded by the TA's based on how helpful and correct it is. Feedback is due in Compass by the date indicated in Table 1. Following the Compass peer review process, you will also provide feedback during the Discussion section indicated in Table 1.

*Final Report*: Once you have received feedback, revise your draft and spreadsheet accordingly. The final report is due by the date indicated in Table 1. *One person from each group* should submit (i) your final report in PDF format and (ii) your final Excel® spreadsheet in Compass by that date.

## 4.6 Launching Mechanism Contest

You will test the launching mechanism you built during the Discussion period indicated in Table 1. In order to receive the associated 10 points toward your project grade, your group must successfully hit a target with a ping pong ball a certain number of times, given the values of $L$ and $H$ (see Figure 2). The group from each Discussion section with the best score will receive an additional prize.

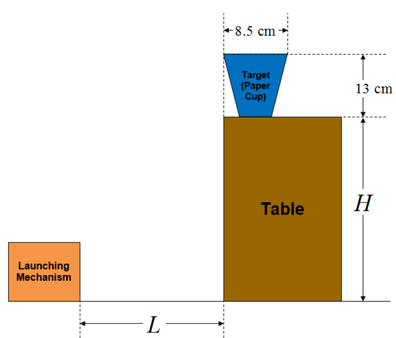


Figure 2: Target schematic, illustrating $L$ and $H$.