Student handout A ping pong ball is thrown from the roof of Weniger Hall with an initial velocity that makes an angle θ up from horizontal. The ball experiences a drag force that is proportional to its velocity.

Use Newton's 2nd Law to solve for the position of the ping pong ball for any value of time.

Hints:

- Consider the horizontal and vertical components of the motion separately.
- While you're planning and working on your solution, be prepared to answer the following questions:
  1. What are you doing right now?
  2. How will the result help you?
  3. How are you checking that the result is sensible?

1 Facilitation

This problem is too long to do in one go. I like to

1. give the prompt
2. let the students work in groups until most groups have thought about finding acceleration components
3. bring everyone together and lead a whole class discussion about finding the acceleration components
4. then let the students return to groups find the velocity components (solve the differential equations)
5. When most groups have finished this part of the problem, discuss the solution as a whole class. If possible, have a group present how they solved for one of the velocity components.
6. Lead a discussion about making sense of the velocity components - dimensions, special cases, graphing the functions and matching it to a conceptual story.
7. Repeat for the position components.

If you want to skips parts, skip position and just ask for velocity.

2 Student Conversations

- **Components:** Most students will already be familiar with needing to break the problem into horizontal and vertical components from Introductory Physics.
- **Direction of the Drag Force:** Most students will need encouragement to draw free-body diagrams for multiple points along the motion to think about how the direction of the drag force changes during the motion. They are used to having a single freebody diagram from introductory physics.
- **Velocity on a Freebody Diagram:** Watch out for drawing the velocity on a free-body diagram. Encourage students to draw the velocity in another color and off to the side to distinguish it.
- **Techniques for Solving Differential Equations:** Some students might recognize (from a differential equations course) that they can solve the with integration factors. This absolutely can be done, but encourage the students to solve by separation to practice.
- **Separating the Vertical Component of Velocity:** Many students have trouble separating the differential equation for the vertical components of the velocity. They want to keep separate the drag and gravity.

$$\frac{dv_y}{dt} + \frac{b}{m}v_y = -g$$

- **Definite Integrals:** Some students will want to do indefinite integrals with integration constants. Encourage them to do definite integrals so that the constant are easier to determine (you don't have to go back and plug in the initial conditions).