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## Air Resistance

When you solve physics problems involving free fall, often you are told to ignore air resistance and to assume the acceleration is constant. In the real world, because of air resistance, objects do not fall indefinitely with constant acceleration. One way to see this is by comparing the fall of a baseball and a sheet of paper when dropped from the same height. The baseball is still accelerating when it hits the floor. Air has a much greater effect on the motion of the paper than it does on the motion of the baseball. The paper does not accelerate very long before air resistance reduces the acceleration so that it moves at an almost constant velocity. When an object is falling with a constant velocity, we describe it with the term *terminal velocity*, or  $v_T$ . The paper reaches terminal velocity very quickly, but on a short drop to the floor, the baseball does not.

Air resistance is sometimes referred to as a *drag force*. Experiments have been done with a variety of objects falling in air. These sometimes show that the drag force is proportional to the velocity and sometimes that the drag force is proportional to the square of the velocity. In either case, the direction of the drag force is opposite to the direction of motion. Mathematically, the drag force can be described using  $F_{drag} = -bv$  or  $F_{drag} = -cv^2$ . The constants  $b$  and  $c$  are called the *drag coefficients* that depend on the size and shape of the object.

When falling, there are two forces acting on an object: the weight,  $mg$ , and air resistance,  $-bv$  or  $-cv^2$ . At terminal velocity, the downward force is equal to the upward force, so  $mg = -bv$  or  $mg = -cv^2$ , depending on whether the drag force follows the first or second relationship. In either case, since  $g$  and  $b$  or  $c$  are constants, the terminal velocity is affected by the mass of the object. Taking out the constants, this yields either

$$v_T \propto m \text{ or } v_T^2 \propto m$$

If we plot mass versus  $v_T$  or  $v_T^2$ , we can determine which relationship is more appropriate.

In this experiment, you will measure terminal velocity as a function of mass for falling coffee filters, and use the data to choose between the two models for the drag force. Coffee filters were chosen because they are light enough to reach terminal velocity in a short distance.

### Objectives

- Observe the effect of air resistance on falling coffee filters.
- Determine how the terminal velocity of a falling object is affected by air resistance and mass.
- Choose between two competing force models for the air resistance on falling coffee filters.

### Materials

TI-82, 83, 86, 89, 92, or 92 Plus  
CBL System  
PHYSICS program loaded in calculator

Vernier Motion Detector  
5 basket-style coffee filters  
Graphical Analysis or graph paper (optional)

## Preliminary questions

1. Hold a single coffee filter in your hand. Release it and watch it fall to the ground. Next, nest two filters and release them. Did two filters fall faster, slower, or at the same rate as one filter? What kind of mathematical relationship do you predict will exist between the velocity of fall and the number of filters?
2. If there were no air resistance, how would the rate of fall of a coffee filter compare to the rate of fall of a baseball?
3. Sketch your prediction of a graph of the velocity vs. time for one falling coffee filter.
4. When the filter reaches terminal velocity, what is the net force acting upon it?

## Procedure

1. Support the Motion Detector about 2 m above the floor, pointing down, as shown in Figure 1.
2. Connect the Motion Detector to the SONIC port of the CBL unit. Use the black link cable to connect the CBL unit to the calculator. Firmly press in the cable ends.
3. Set up the calculator and CBL for the Motion Detector. Start the PHYSICS program and proceed to the MAIN MENU.
  - Select SET UP PROBES from the MAIN MENU.
  - Select ONE as the number of probes.
  - Select MOTION from the SELECT PROBE menu.
4. Set up the calculator and CBL for data collection, and then collect data.
  - Select COLLECT DATA from the MAIN MENU.
  - Select TIME GRAPH from the DATA COLLECTION menu.
  - Enter "0.03" as the time between samples, in seconds.
  - Enter "99" as the number of samples (the CBL will collect data for about 3 seconds).
  - Press , then select USE TIME SETUP to continue. If you want to change the sample time or sample number, select MODIFY SETUP instead.
5. Place a coffee filter in the palm of your hand and hold it about 0.5 m under the Motion Detector. Do not hold the filter closer than 0.4 m.
6. Press  to begin data collection. When the Motion Detector begins to click, release the coffee filter directly below the Motion Detector so that it falls toward the floor. Move your hand out of the beam of the Motion Detector as quickly as possible so that only the motion of the filter is recorded on the graph.

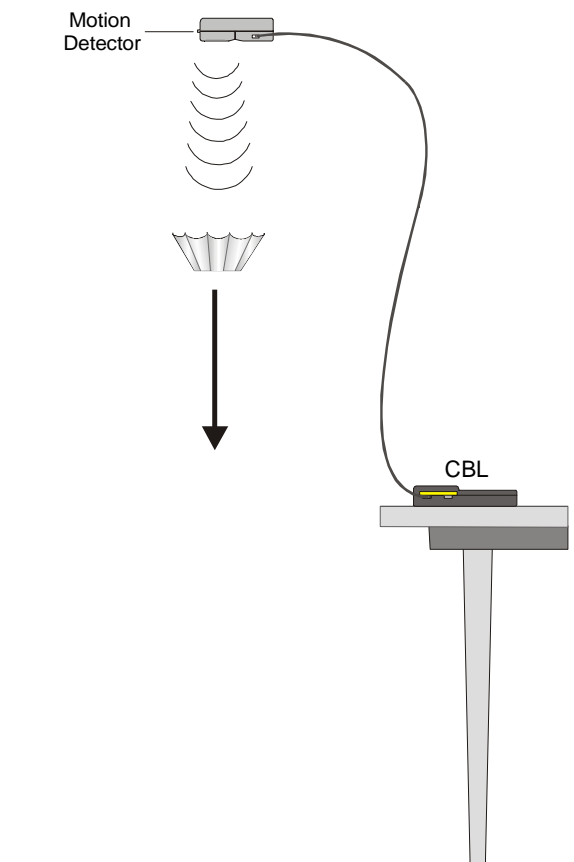


Figure 1

## 7. View your distance graph.

- Press  to view the SELECT GRAPH menu.
- Select DISTANCE to view the distance graph.
- If the motion of the filter was too erratic to get a smooth graph, repeat the measurement. With practice, the filter will fall almost straight down with little sideways motion.
- Press  and select NEXT.
- Select NO to continue, or YES to repeat data collection.

8. The velocity of the coffee filter can be determined from the slope of the distance vs. time graph. At the start of the graph, there should be a region of increasing slope (increasing velocity), and then the plot should become linear. Since the slope of this line is velocity, the linear portion indicates that the filter was falling with a constant or terminal velocity ( $v_T$ ) during that time. To fit a line to only the linear region,

- Select ANALYZE from the MAIN MENU.
- Select SELECT REGION from the ANALYZE MENU.
- Select DISTANCE from the SELECT GRAPH menu.
- Move the flashing cursor with the cursor keys to the left edge of the linear region corresponding to the filter in motion at constant speed, and press .
- Move the flashing cursor to the right edge of the linear region, and press .
- View your abbreviated graph by selecting DISTANCE from the SELECT GRAPH menu. You should see only the linear region.
- Press , and select NEXT.
- Select ANALYZE from the MAIN MENU.
- Select CURVE FIT from the ANALYZE MENU.
- Select LINEAR L1, L4 from the CURVE FIT menu.
- Record the slope in the data table (a velocity in m/s).
- Press  to see the fit along with your data.
- Press  to return to the MAIN MENU.

## 9. Repeat Steps 4 – 8 for two, three, four, and five coffee filters. (Optionally extend to six, seven and eight filters, but be sure to use sufficient fall distance so that a clear velocity can be measured.)

**Data Table**

| Number of filters | Terminal Velocity<br>$v_T$ (m/s) | (Terminal Velocity) <sup>2</sup><br>$v_T^2$ (m <sup>2</sup> /s <sup>2</sup> ) |
|-------------------|----------------------------------|---|
| 1                 |                                  |   |
| 2                 |                                  |   |
| 3                 |                                  |   |
| 4                 |                                  |   |
| 5                 |                                  |   |

## Analysis

1. To help choose between the two models for the drag force, plot terminal velocity  $v_T$  vs. number of filters (mass). On a separate graph, plot  $v_T^2$  vs. number of filters. Use your calculator, Graphical Analysis, or graph paper. Scale each axis from the origin (0,0).
2. During terminal velocity the drag force is equal to the weight ( $mg$ ) of the filter. If the drag force is proportional to velocity, then  $v_T \propto m$ . Or, if the drag force is proportional to the square of velocity, then  $v_T^2 \propto m$ . From your graphs, which proportionality is consistent with your data; that is, which graph is closer to a straight line that *goes through the origin*?
3. From the choice of proportionalities in the previous step, which of the drag force relationships ( $-bv$  or  $-cv^2$ ) appears to model the real data better? Notice that you are choosing between two different descriptions of air resistance—one or both may not correspond to what you observed.
4. How does the time of fall relate to the weight ( $mg$ ) of the coffee filters (drag force)? If one filter falls in time,  $t$ , how long would it take four filters to fall, assuming the filters are always moving at terminal velocity?

## Extensions

1. Make a small parachute and use the Motion Detector to analyze the air resistance and terminal velocity as the weight suspended from the chute increases.
2. Draw a free body diagram of a falling coffee filter. There are only two forces acting on the filter. Once the terminal velocity  $v_T$  has been reached, the acceleration is zero, so the net force,  $\Sigma F = ma = 0$ , must also be zero

$$\Sigma F = -mg + bv_T = 0 \quad \text{or} \quad \Sigma F = -mg + cv_T^2 = 0$$

depending on which drag force model you use. Given this, sketch plots for the terminal velocity ( $y$  axis) as a function of filter weight for each model ( $x$  axis). (Hint: Solve for  $v_T$  first.)