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 air resistance and mass affect the terminal velocity of a falling object.
Choose between two competing force models for the air resistance on falling coffee filters.

MATERIALS

LabPro or CBL 2 interface	Vernier Motion Detector
TI Graphing Calculator	5 basket-style coffee filters
DataMate program	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 DIG/SONIC or DIG/SONIC 1 port of the LabPro or CBL 2 interface. Use the black link cable to connect the TI Graphing Calculator to the interface. Firmly press in the cable ends.

3. Turn on the calculator and start the DATAMATE program. Press CLEAR to reset the program.

4. 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.

5. Select START to begin data collection. After the interface beeps, 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.

6. View your distance graph.

    a. Press ENTER to view the distance graph.
    b. If the motion of the filter was too erratic to get a smooth graph, you will need to repeat the measurement. With practice, the filter will fall almost straight down with little sideways motion.
    c. Press ENTER and select MAIN SCREEN.
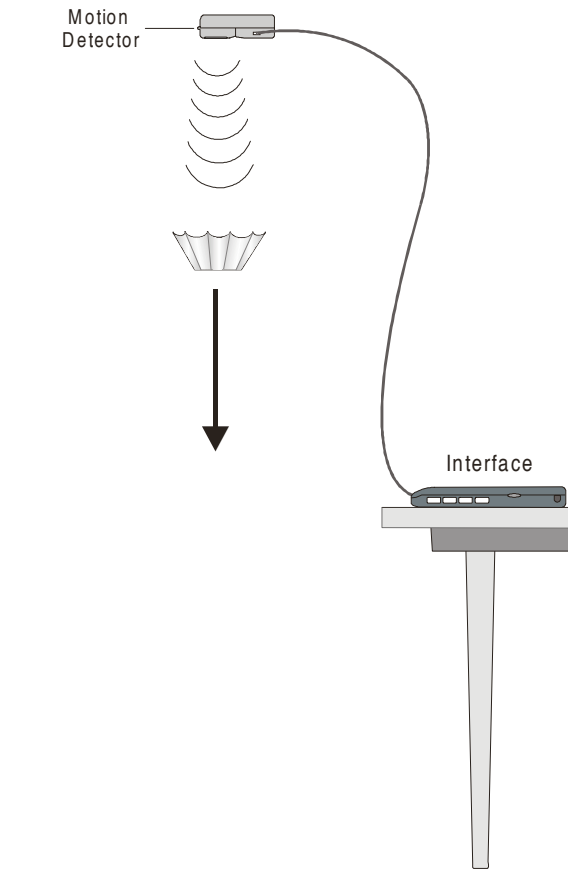   d. Repeat data collection as necessary.

Figure 1

7. 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 the linear region, you first need to select that portion of your data.

   a. Select GRAPH from the main screen.
   b. To select just the linear portion of the distance graph, select SELECT REGION.
   c. Move the flashing cursor with the ◀ and ▶ keys to the left edge of the linear region corresponding to the filter in motion at constant speed and press ENTER.
   d. Move the flashing cursor to the right edge of the linear region, and press ENTER.
   e. View your abbreviated graph by pressing ENTER. You should see only the linear region.
   f. Select MAIN SCREEN to return to the main screen.

8. Fit a straight line to the region you just selected.

   a. Select ANALYZE from the main screen.
   b. Select CURVE FIT from ANALYZE OPTIONS.
   c. Select LINEAR (DIST VS TIME) from the CURVE FIT screen.
   d. Record the slope in the data table (a velocity in m/s).
   e. Press ENTER to see the fit along with your data.
   f. Press ENTER, and select RETURN TO MAIN SCREEN.

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 v_T (m/s)	(Terminal Velocity)^2 $v_T{}^2$ (m^2/s^2)
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

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

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.)

TEACHER INFORMATION

Air Resistance

1. The experiment can also be performed by placing the Motion Detector on the floor and dropping the filters directly over it. Setup is much easier, but the graphs may be hard for students to interpret since readings will be unreliable after the filter is closer than 0.40 m.

2. Larger food-service size coffee filters of roughly the same proportions as consumer basket style coffee filters are available. Try to get some of these from a restaurant or your cafeteria. They make great demonstration devices.

3. There are numerous articles on the physics of air resistance. Two recent references from *The Physics Teacher* references are "Modeling Air Drag," by Christopher Brueningsen, *et al*., Volume 32, October 1994, page 439 ff, and "Effects of Air Resistance," Vasilis Pagonis, *et al*., Volume 35, September 1997, page 364 ff.

4. Students need to recognize that during free fall the drag force is equal to the weight of the filters; therefore, the weight of the filters or number of filters equal drag force during terminal velocity. Best results are obtained by allowing the filters to fall a long distance. Consider having the students stand on a chair when releasing the filters.

5. You may want to have students use a higher data collection rate than the default 0.05s sample time used in the instructions. (The TI-73 uses a longer sample time.) Set the data collection rate using these steps:

   a. Select SETUP from the main screen.
   b. Use the ▲ and ▼ keys to move the cursor to MODE, and press ENTER.
   c. Select TIME GRAPH from SELECT MODE.
   d. Select CHANGE TIME SETTINGS from the TIME GRAPH SETTINGS screen.
   e. Enter "0.02" as the time between samples. (Use "0.05" if you are using a TI-73.) Remember to finish your entry with ENTER.
   f. Enter "150" as the number of samples. (Use "50" if you are using a TI-73, or "100" if you are using a TI-83.)
   g. Select OK.
   h. Select OK a second time to return to the main screen.

SAMPLE RESULTS
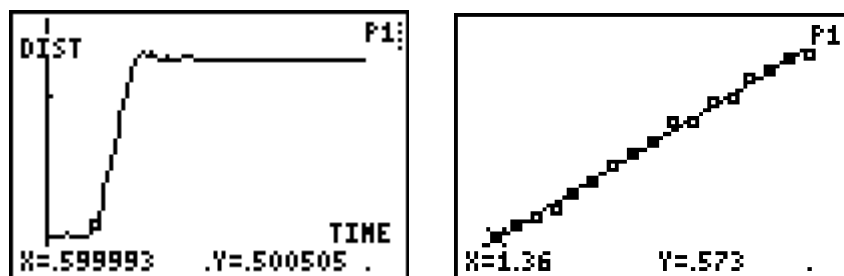
*Typical distance vs. time graphs showing all data and selected region only.*

Number of filters	Terminal Velocity v_T (m/s)	(Terminal Velocity)^2 v_T^2 (m^2/s^2)
1	1.39	1.93
2	1.94	1.25
3	2.16	1.88
4	2.59	2.46
5	2.77	3.50

ANSWERS TO PRELIMINARY QUESTIONS

2. Two filters fall more quickly than one filter. The rate of fall will increase with the number of filters nested.

3. Without air resistance, a baseball and a coffee filter would fall at the same rate.

4. (sketch)

5. At terminal velocity, air resistance matches the downward force, so there is no net force.

ANSWERS TO ANALYSIS QUESTIONS

1. Two different models for the drag force:
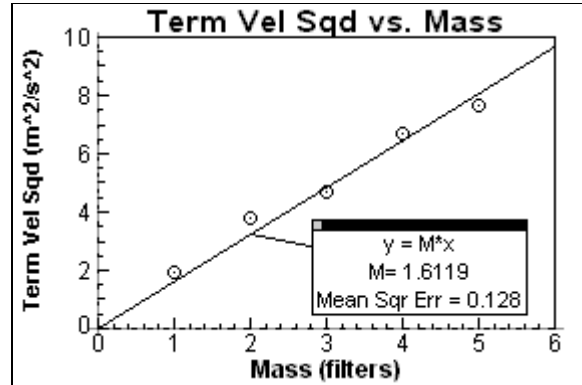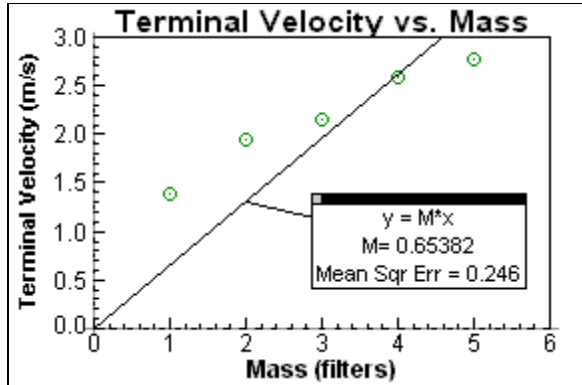
2. The graph of v_T^2 vs. mass is closer to a direct relationship than is the graph of v_T vs. mass. In particular, the v_T^2 vs. mass graph points toward the origin, while the v_T vs. mass does not. The v_T vs. mass graph is also more curved than the v_T^2 vs. mass graph.

3. Since the v_T^2 vs. mass graph is close to a proportionality, it appears that the drag force is proportional to the square of velocity, or $F_{drag} = -cv^2$.

4. Since our graphs show that terminal velocity squared is directly proportional to mass, the terminal velocity of four filters is about twice as large as the terminal velocity of one filter; therefore, the fall would take half as long.