3a. THE BEHR FREE FALL EXPERIMENT

Note: An alternative Behr free fall lab can be found at the end of this one. It is less involved and may be more approachable than the following. See your instructor to find which of the two labs you are to do.

Equipment List:

- One Behr Free Fall Apparatus and spark timer (A back-up unit is desirable).
- One two-meter stick per table.
- Masking tape.
- Red wax paper tape with Behr Free Fall data on it produced by the apparatus.

What you will do:

By a graphical method, you will find the instantaneous speed of a falling object at three different times during its flight (this is part I). Then, by a different graphical method, you will find each of those three speeds with three other graphs, one graph for each speed (parts II, III, and IV). The three speeds in part I should match the corresponding speeds found in parts II, III, and IV.

Introduction:

The Behr Free Fall apparatus produces a written record of a freely falling object's position ***at equal intervals of time***. The falling object is called the "bob". The bob falls a distance of about five or six feet. Falling from rest this would allow for a total time of flight of: $t = [2y/g]^{1/2}$ 0.6 seconds (derive and confirm this). Since the bob is in flight for about half a second, for the bob to leave a trace of its position at equal intervals of time, the intervals of time must be very short. These small time intervals are produced by a "spark timer".

A spark timer is a high voltage mechanism that produces a spark which, as the bob falls, arcs across the bob and through a waxed paper tape making a small burn hole (a dot) in the paper. To produce the thirty or so total dots in the paper when only a total time of 0.6 seconds is allowed, sparks must be generated every one sixtieth of a second. We will assume the spark timer produces a spark *exactly* every one sixtieth of a second. **So each dot is separated by an equal interval of time.**

Although the initial speed of the bob is zero (it *does* fall from rest), the first dot produced on your paper tape is *not* created while the bob is at rest. Since the bob has to travel some distance from its rest position to where the first dot is made, the bob must have a non-zero speed when the first dot is created. We will determine this initial speed.

Since it is difficult to produce an arc through the paper, every now and then your paper tape may have a dot (or many dots) missing. When you receive your paper tape, inspect it immediately for missing dots. You should have thirty dots on your paper. Even if you are missing some dots, your paper tape may still be usable as discussed below. What really matters is that you have at least five positions each separated by equal intervals of time.

Procedure:

1. Under the direction of your instructor, obtain one red paper tape of a "run". Check the tape and replace it if there are dots missing. Be careful during the operation of the apparatus since **very high voltage** is used to create the arc that burns the wax paper tape.

2. With the masking tape provided, tape down each end of the paper tape on your lab table so that it is taut and lies flat with the light colored side facing up showing all the small burned dots.

3. Starting from the beginning of the tape where the dots are close together, draw a circle around the first dot and then every *sixth* dot after that for a total of **five** circled dots.[(2)] Be careful circling your dots; it is easy to miss one and that would throw all your data measurements off. **These five circled dots will be your only data points for the *entire* experiment.** Since you are not using all thirty dots produced by the apparatus, you need not have all thirty dots present on your paper tape for it to be acceptable. Your instructor may help determine if your paper tape is still acceptable with some missing dots.

4. On the paper tape, label each of the five circled dots X_0

through X_4. Where X_0 refers to the *first* dot made by the spark.

For each circled dot, draw a thin line through the dot such that the line is perpendicular to the lengthwise direction of the tape. Draw the line across the entire width of the tape (see figure 1, above).

5. **Please read this next section entirely before recording any data.**

Take your two-meter stick and place it *on edge* (to minimize parallax error) aligning it with the length of the paper tape. Place the meter stick near the dots but do not cover the dots. The meter stick should be kept parallel to the line made by all thirty dots. If no two-meter sticks are available, you will have to use a one-meter stick and move it as necessary. Do not place the meter stick at a pre-chosen position like its end edge or the one centimeter mark, doing so merely prejudices your data measurements, something to be avoided. Place the meter stick down at an arbitrary position so the position of the first dot will be the smallest value of your five positions but not some "even" or easy-to-read value.

Draw a position versus time graph *while you take each data point* and check to see if you have skipped any dots. Before you start taking your data, plan the scale of your graph so that it will cover at least a half page of your lab book. Relative to the meter stick, note the positions of the first and last circled dots so you can approximate the vertical axis scaling, and for the horizontal axis scaling, recall that the time interval between each circled dot is 0.1 seconds. You will know if you skipped any dots if the curve described by the data points becomes non-parabolic. **Record *and graph* the position of the five circled dots.** You should interpolate the measurement on your meter stick to read positions to the one hundredth of a centimeter. Write down the absolute uncertainty associated with your measurement. Let the first position be graphed at time t = 0; the first position itself should not be a zero value but should be the value you measured on your meter stick.

Analysis:

Part I: Finding instantaneous speeds from a tangent line on a position versus time graph. On your position versus time graph drawn while you took your data, use your ruler to draw an "eyeball" tangent line to the parabolic curve at each position X_0, X_2, and X_4. Measure the slope of each of your three straight lines. Interpret the physical meaning of each line.

<u>Part II:</u> Finding the instantaneous speed V_0 at the initial position X_0 and calculating g.

The following method is important to understand as it forms the basis for the analysis of parts II, III, and IV.

The goal of this analysis is to show a limit process by graphical methods and, by *extrapolating* the graph, to find an instantaneous speed. In this part we will also determine the value of *g* from the graph.

We know the definition of instantaneous speed as a limit:

If we plot **average speeds** on the y-axis and corresponding **time intervals** on the x-axis, then it is possible to see that the average speed approaches an instantaneous speed as the time intervals approach zero. On the graph the time intervals approach zero as the data points approach the vertical axis. Understand that this kind of graph is *not* the classic *instantaneous* speed versus time graph that is typically discussed in kinematics; the graph we will use is an *average* speed versus a time *interval*. Study the graph on the next page to help understand this.

As an example, a sample data/calculation table for a hypothetical Behr Free Fall experiment is given on the next page. The acceleration that produced this data is not equal to *g* and the time interval between dots is 0.5 seconds not 0.1, but the calculations used are identical to those needed in constructing your graphs. These calculations would be used to find the initial instantaneous speed V_0 at the position X_0. When you graph $_{ij}$ versus t_{ij} (you will have four data points to graph from *five* measured positions) a linear relation should be observed.

From the table, you should observe that the first average speed is calculated between the first two circled dots at positions 2.25 and 2.53 cm. Since the time interval between these positions is half a second, the average speed is:

$$_{01} = (X_1\text{-}X_0)/t_{01} = (2.53\text{-}2.25)/0.5 = 0.56 \text{ cm/s}$$

You should confirm the other calculations in the table to test your understanding. Your graph is a graph of $_{ij}$ versus t_{ij}. Notice that in calculating the different average speeds the position of the dot where we want to find the instantaneous speed is always part of the calculation. Notice also that the average speeds increase as the position between the dots increases and the time interval between the dots increases; this is natural since the bob *is* speeding up as it falls - its average speed is increasing.

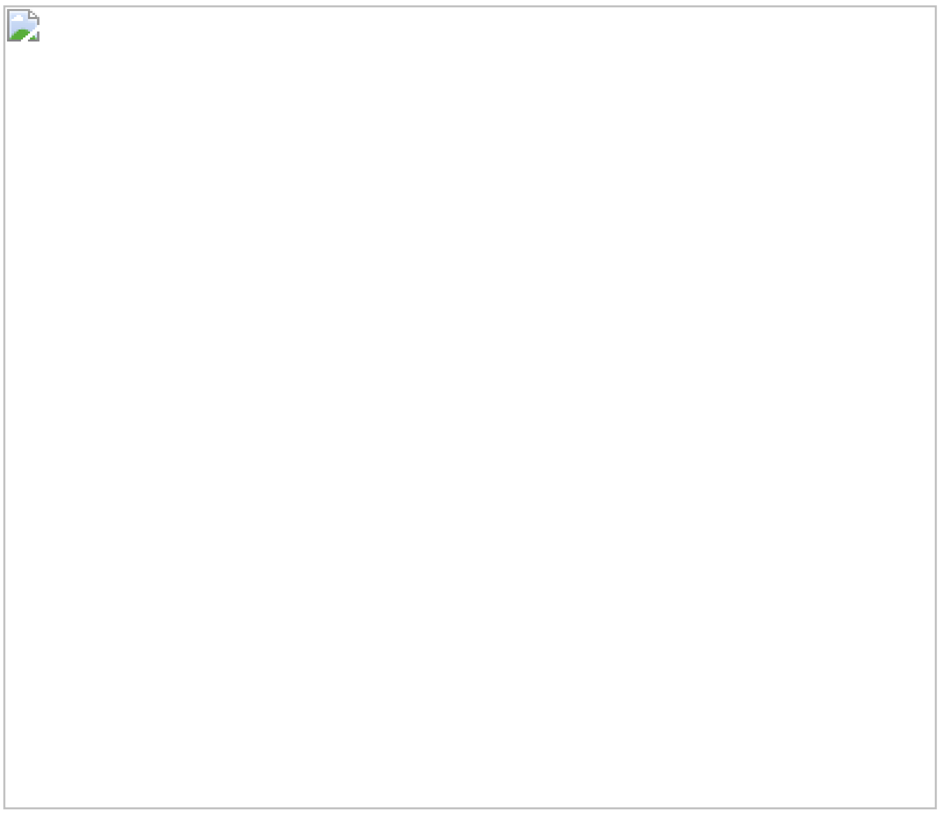
To further aid your understanding, the next data point in the graph would be calculated as follows:

$$_{02} = (X_2 - X_0)/t_{02} = (3.35-2.25)/1.0 = 1.10 \text{ cm/s}$$

Sample data/calculation table.

X_i (cm)	t_i (s)	$_{ij}$ (cm/s)	t_{ij} (s)
2.25	0.0	----	----
2.53	0.5	$V_{01} = 0.56$	0.5
3.35	1.0	$V_{02} = 1.10$	1.0
4.73	1.5	$V_{03} = 1.65$	1.5
6.65	2.0	$V_{04} = 2.20$	2.0

From your graph determine the initial speed of the bob, V_0, at the first position X_0. Also from the slope of your graph calculate *g* (see the theory section below). Compare your calculated value of *g* with the known value using a discrepancy test.



Theory exercise: Using kinematics, show that versus t is linear. As part of the derivation of your equation, show how the slope of this graph is related to the acceleration of the falling body. Interpret the physical meaning of the y-intercept.

Part III: Finding the instantaneous speed of the bob at its final position. Repeat the methods of part II to find the instantaneous speed V_4 at the position X_4. To find the instantaneous speed at the final position, hold the final position constant while varying the other position and time values.

Part IV: Find the instantaneous speed V_2 of the bob at the time midpoint t_2 at the position X_2. Again use the methods previously developed. In this part however, as you shrink your time intervals *no* positions are held constant. Think symmetry, and see if you can figure it out.

Part V: Compare the three instantaneous speeds found in part I to those found in parts II, III, and IV. Also, can you calculate *g* from the graphs in parts III and IV? Error analysis has been ignored, how could you apply it meaningfully to this experiment?

Part VI: Show mathematically (i.e., algebraically with no numbers) that the average speed over a time interval is equal to the instantaneous speed at the *midpoint* of that time interval if the acceleration is constant. Confirm this principle by taking the average speed $(V_0 + V_4)/2$ and comparing the result to the instantaneous speed value V_2 at the time midpoint as calculated in Part I *and* Part IV.