# Lab 2: Free-Fall

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## INTRODUCTION

How do objects in free-fall move? Do they move at a steady—***constant***—speed? Or do they get faster or slower (accelerate) as they fall? If they do accelerate does the rate of acceleration stay constant. . . or does that change too—in other words, does the acceleration get bigger/smaller over time? And if the acceleration is changing over time, does it keep changing at a steady rate, or is that rate changing too? Etc.

In this experiment, we will try to answer these questions.

In order to do so, we will drop long, vertical strings with machine screws attached at various intervals along the string from heights of 3-5 meters and listen to the timing (rhythm) of the screws as they hit a metal tray at the bottom of their fall.

## OBJECTIVES

In plain English:
*to determine how falling objects move.*

In more complicated (but also more precise) English:
*to analyze the behavior of falling objects in terms of the derivatives (first, second, etc.) of position with respect to time.*

An object is said to be in free-fall whenever there is nothing *holding it* or *pushing it*. Anything flying through the air, whether it was thrown or dropped, is in free-fall (as long as it does not have jet-packs or propellers and air-resistance is negligible).

## WHAT WE KNOW

- The definitions of distance & displacement.
- The definitions of average speed & average velocity.

## WHAT WE DON'T KNOW

Everything else.

**PROCEDURE**

**A.** Creating and Testing an Evenly-Spaced String

1. Cut a string approximately 5 meters in length.

2. With a ruler and pencil, mark off 5 to 10 ***equally spaced*** positions. The first mark should be all the way at one end of the string. (Within the range of 5-10, it's up to you how many positions you mark. The more positions, the more data points. The more data points, however, the less clearly distinguishable they become.)

3. Using ***SLIPKNOTS***, attach a machine screw at each of the marked-off positions.

4. Wait for all other groups to complete step ***3***. While waiting, ***read ahead.***

5. Once all groups are ready, each group will go one at a time and drop its ***spatially symmetric*** string from a high location (approximately 5 meters) onto a cookie sheet. All other groups will quietly watch, listen and record.

6. Your lab instructor will lead you to this location. At this location, we will conduct ourselves in a singularly quiet and reserved and careful manner. We will otherwise be creating a hazard.

7. Listen closely to the pattern of sounds made by the screws as they slam into the cookie sheet. With a cell phone or hand-held digital recorder, record them. If you have ***slow motion*** on your recording device, use it.

**B.** Analyzing Data from the Evenly-Spaced String.

1. Listen to your recording and discuss what you hear.

***As a group***, ***write down*** your answers to the following questions:

2. What happens to the beats (sounds of the screws striking the cookie-sheet) as the string falls?

3. What happens to the time interval between each beat, as the string falls?

4. How far did the screws fall in between the first beat and the second? How far did they fall between the second beat and the third? The third and the fourth? Etc.

5. Given the pattern in the distance traveled between beats (question B.4) & the pattern in the time interval between beats (question B.3), what must be happening to the ***average speed*** between each beat, as the string falls?

**C.** Searching for the Evenly-Timed String

Now we're going to create some more strings and drop them in the same manner that we dropped the first one.

> THE GOAL: attach the screws to the string in such a way that they create a ***steady rhythm*** as they land. In other words, the ***time*** in between the beats should stay the same as the string falls.

We will start out experimenting with ***shorter strings*** of 2.8 meters, which can be tested in the classroom. Once you have a pattern that you believe works, you will create a 5-meter string and drop it in the stairwell.

1. Cut a string 2.8 meters long (more or less).

2. With pencil and paper, spend time CAREFULLY contemplating where on the string you believe machine screws ought to be placed in order to meet The Challenge described above.

   Without actually dropping any string, ***clearly write out all your thoughts***. They may be words, numbers, equations, etc. NO THOUGHTS, however, may be used without *specific* ***justification***. An isolated equation that you may have seen or memorized is NOT itself a justification.

   **Hint 1:** Go back to the recording you made of the evenly-spaced string drop. What must you do in order to make the time intervals equal?

   **Hint 2:** On of the basic assumptions of physics (and science in general) is that the world is full of ***mathematical patterns***. That might be a good thing to keep that in mind when designing your string.

   **Hint 3:** You want your top-most screw to be close to the top of your string. If ALL the screws are near the bottom, the rhythm will be very fast and difficult to hear clearly.

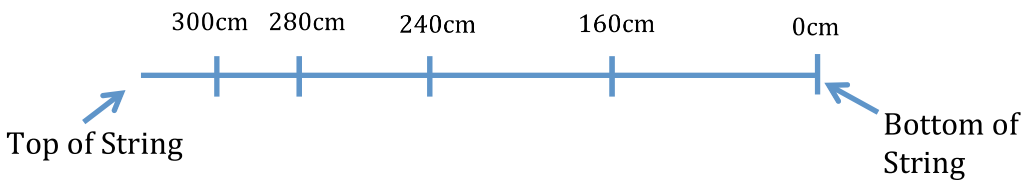
3. When you have arrived at a clear decision, ***before you do any testing***, you must draw ***TWO*** diagrams to show your pattern of screw placements: we call these the ***interval*** diagram and the ***position*** diagram.

   The ***Interval*** Diagram shows the distances ***BETWEEN*** the screws.

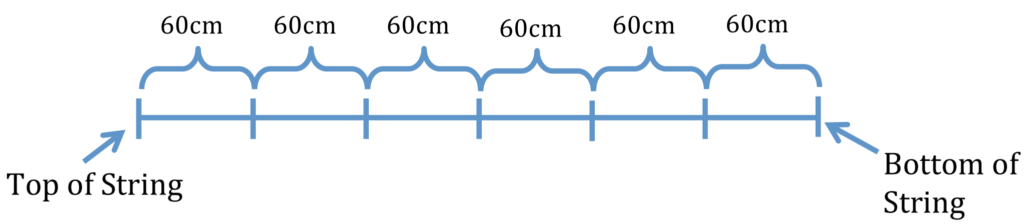
   The ***Position*** Diagram shows the ***total*** distance ***from*** each screw ***to the bottom of the string***.

   To help you get the hang of position & interval diagrams, **PLEASE COMPLETE THE TWO EXERCISES BELOW:**

**Exercise 1:** below is a ***Position Diagram*** of a string with 5 screws on it. Convert this into an interval diagram.




**Exercise 2:** below is an interval diagram of a string with 7 screws on it. Convert this into a position diagram.




4. ***After you come up with your plan*** for your evenly-timed string, but ***before you attach the screws***, show your work (including both a position and an interval diagram) to your lab instructor.

5. As you did in part A, measure and mark your string according to the pattern you have selected and use slipknots to attach the screws.

6. When your string is ready, one lab-group-member should stand on top of the lab table, holding the string vertically over a small round string.

7. Record (ideally in slow-motion) and listen closely to the pattern of sounds made by the screws as they slam into the cookie sheet. Play the sound for your lab instructor, and explain to him/her your pattern, if you did not already.

8. Did you achieve an steady rhythm? If not, think about the rhythm you created and come up with a new pattern. Feel free to discuss with your instructor.

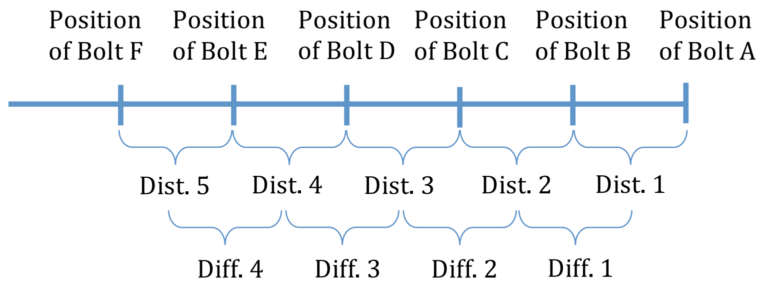
   If you & your instructor agree that your pattern sounds good, create a 5-meter version of the same pattern. Try to fill up the 5-meter string as you did with the 2.8-meter string. Test this string in the stairwell.

9. Before the second day of this lab is over, your instructor will give you ***two mathematical patterns***. We will call these patterns pattern A and pattern B. You will find out what they are during the course of the lab. You will make 5-meter strings based on these patterns and drop them from the stairwell.

**D.** Mathematical Analysis of Patterns.

1. For Pattern A:
    a. Draw a position diagram. Make sure to include at least 6 screws.
    b. Below the position diagram, write down the distances between screws (i.e. the intervals).
    c. Below the distances, write down the ***differences between the distances***.
    d. Below the differences between distances, write down the ***differences between the differences between distances***.
    e. What do you notice?

Your work will look something like this:




(it's ok if you can't make those cool little  shapes.)

2. For pattern B:
    a. Draw a position diagram. Make sure to include at least 6 screws.
    b. Below the position diagram, write down the distances between screws (i.e. the intervals).
    c. Below the distances, write down the ***differences between the distances***.
    d. Below the differences between distances, write down the ***differences between the differences between distances***.
    e. What do you notice?

3. Now try this same type of analysis for a type of pattern that comes up a lot in both science and mathematics: an exponential pattern. Use the simplest exponential pattern: 1, 2, 4, 8, 16, 32, etc. Follow the same steps a., b., c., d., etc. that you used for the other two patterns, and keep going until you see how this pattern is different from the other two. Will this process ever end?

**E.** Drawing Conclusions about Motion in Free-Fall.

We will assume from here on out that one of the patterns you tested produced a fairly steady rhythm. (If you did not find any pattern that produced a fairly steady rhythm, check in with you lab instructor.)

We are now going to use the pattern that you found (and the fact that it made a steady rhythm) to figure out ***how gravity affects objects in free fall***.

Remember, up to this point in the semester, the only thing we know about gravity is that when you drop something it falls. But what does it do when it falls? That's what we're here to figure out

1. Your pattern produced a ***steady rhythm***. Just to recap, that means that the time interval between beats stayed ____________________ for each pair of beats.

   Hm… An interval of time that stays ***consistent***. Meaning it doesn't ***change***, as the thing falls. Hm. That ***reminds*** me of something… something from ***LAB 1***. That sounds like a… a… u n i t o f m e a s u r e m e n t !!!

2. Here's the plan. We want to know how about the motion of objects during free fall. In particular, we want to know whether their ***speed*** is ***changing***, and if it's changing, ***how*** it's changing. Well, instantaneous speed might be tricky, but we know how to calculate ***average*** speed. Write down the definition of average speed.

3. Calculate the distance traveled by the bolts between each pair of beats. (You've already figured this out; yes, it's that simple.)

4. Calculate the ***average speed*** of the bolts between each pair of beats. (If you had $n$ bolts on your string, you should end up with $n$-1 average speeds.) Your answers should be in cm/beat (or m/beat). Notice that we don't know how many seconds = 1 beat. Notice that this does not matter.

5. Calculate the ***change*** in average speed from beat to beat. In other words, calculate the change in average speed ***over time***.

   What units should this be in?

   ***Hint:*** Think about the units you used for average speed. Then think about the fact that this is change in average speed ***over time***.

6. What conclusion can you draw about the motion of objects in free fall? Does their speed stay the same as they fall or does it change (accelerate)? If their speed changes, does their acceleration change (jerk)? If their acceleration changes, how does it change?

   ***Hint:*** think back to The Great Dog Race. In that problem, you used the same method of comparing average speeds to approximate acceleration.

**F.** A Hypothetical Scenario

In order to better understand your data and your conclusion, perform the following thought experiment.

1. Imagine that you are in an alternate universe with different laws of physics. In this universe, when you dropped a string with ***Pattern B***, it produced a steady rhythm.

2. Do the same analysis you did in part E (especially steps 3-5) for Pattern B.

3. Calculate the ***change in the change in*** the average speed, during each beat. What units would ***this*** be in?

4. What conclusions would you draw about the motion of objects in free-fall in this imaginary alternate universe? Does their speed stay the same as they fall or does it change (accelerate)? If their speed changes, does their acceleration change (jerk)? If their acceleration changes, does it go up or down? Does their jerk change too, or is that constant?