

LAB I. FREE FALL MOTION

1. Objectives

The purpose of this lab is to use the one-dimensional motion principle to estimate the acceleration as an object falls toward ground. Then, to make the comparison with the gravitational acceleration of earth. The data obtained in this lab can also be used to test the conservation of mechanical energy later in Lab VIII.

In this lab, you will get familiar with the Tracker software and learn how to obtain physical properties including position and velocity of an object from recorded videos. In addition, you will learn the basic data analysis strategies, such as performing statistics, plotting data points, and fitting linear or quadratic functions.

2. Materials (see **Fig. 1**)

- A meterstick/ruler
- A golf/tennis/ping-pong ball or other preferably regular objects
- Poster strip tape
- A smartphone
- A smartphone tripod

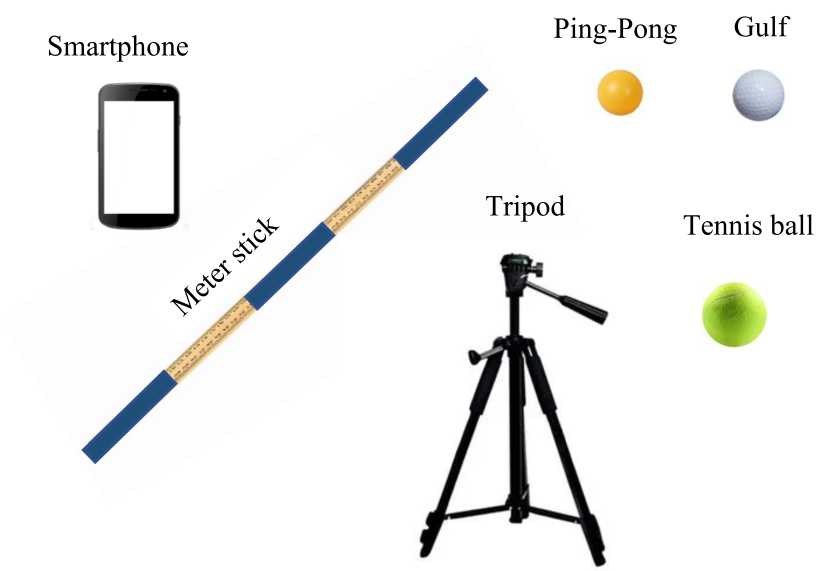

Fig. 1 A list of materials used in this lab.

3. Theory

Figure 2 shows the expected motion behavior of free fall and the definition of the coordinate system. The time difference between the small balls is the same but the distance is longer when the ball is closer to the ground. This shows that the ball travels faster as it moves downward. Consider a single point object moving along a straight line with a constant acceleration a. The position of the object at time t follows,

$$y = y_0 + v_0(t - t_0) + \frac{1}{2}a(t - t_0)^2, \quad (1)$$

where y and y_0 are the instantaneous (at time t) and initial (at time t_0) displacement (this should be position, not displacement) of the point mass, and v_0 is the initial velocity at time t_0, The velocity of the object at time t is given by,

$$v = v_0 + a(t - t_0). \quad (2)$$

Ignoring air resistance, a dropping object falls with a constant acceleration known as g or gravitational acceleration. For free fall, no x-displacement is expected. Therefore, by analyzing the location-time dependent data extracted from the lab, you shall be able to obtain an accurate measurement of g.

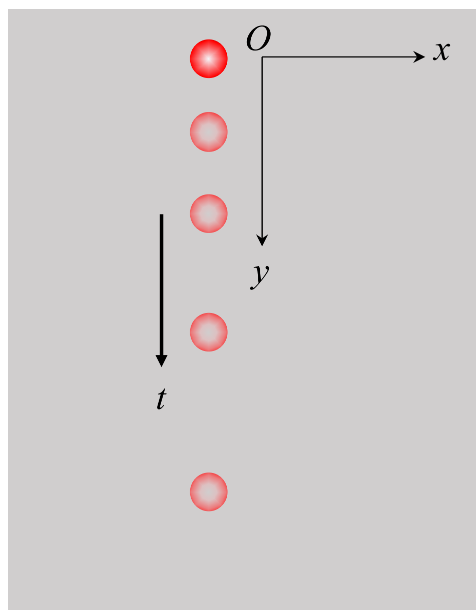

Fig. 2 A ball is moving faster closer to ground.

4. Lab Setup Preparation

There are several instructional videos on the preparation of the lab. You need to watch

(1) **Preparing the Meterstick** video (https://www.youtube.com/watch?v=67j4kJOiAQI)

(2) **Phone Setup** video (https://www.youtube.com/watch?v=nHfeejFBe28)

(3) **Tracker Tutorial** video

(https://www.youtube.com/watch?v=BxplFubEVzQ)

Please make sure that you follow the detailed instructions to avoid potential errors in data analysis before attempting to perform the experiment. Here, important notes on the setup preparation are described in detail.

5. Experiment & Data Analysis Procedure

A detailed video instruction on how to perform the free fall can be found at https://www.youtube.com/watch?v=UqsDpW3ypEw&t=104s.

5.1 *Experiments*: Record 5-10 different videos of free fall motion.

5.2 *Raw data extraction*: Use Tracker to obtain the position of the free fall object as a function of time in both *x*- and *y*-directions and export the data to Excel files.

5.3 *Horizontal position statistics*: Perform statistics analyses on the *x*-position data to determine whether you need to redo the experiments or Tracker analysis. If the standard deviation in the *x*-direction σ_x is negligible (i.e., $\sigma_x \leq 0.001$ m), you are following the procedure correctly; otherwise, either the coordinate system was not set appropriately in the Tracker analysis, i.e., it may be rotated, or the ball was dropped with an initial horizontal velocity, i.e., the ball was performing a slightly projectile motion. For the latter two cases, you either need to re-analyze the video or re-do the experiment.

5.4 *The $y(t)$ plots and data analysis*: Plot the position *y* of the free fall object as a function of time *t* and investigate the *y*-*t* plots. Based on equation (1), the position *y* of an object in a constant acceleration 1D motion is a quadratic function of time *t*, and it can be rewrite as,

$$y = A + Bt + Ct^2, \quad (3)$$

Fit a quadratic function to your *y*-*t* data based on the instruction for **Plotting and Fitting,** and obtain the corresponding v_0 and *g* for each video, and perform a statistic analysis of the obtained v_0 and *g* from the 5-10 videos.

5.5 *Direct velocity extraction and plots*: The *y*-*t* data set from each video can be represented by a discretized data set (y_i, t_i), where *i* is an integer and represents the number of the *y*-*t* data extracted from Tracker for the same motion video, $1 \leq i \leq N$. Here *N* is the total number of data extracted. Mathematically the instantaneous velocity for a motion can be expressed as $v(t) = \lim_{\Delta t \to 0} \frac{y(t+\Delta t) - y(t)}{\Delta t}$. Thus, for the discretized data set (y_i, t_i), the instantaneous velocity $v(t_i)$ can only be obtained numerically as,

$$v(t_i) = \frac{y_{i+m} - y_{i-m}}{t_{i+m} - t_{i-m}}, \quad (4)$$

where *m* is an appropriate and small integer number ($m < 10$) depending on the frame rate of the video taken, and the size or resolution of the video. According to **Excel Data Process** instruction, for a selected video, plot the velocity $v(t_i)$ versus t_i for different *m*. Perform the linear curve fitting for all the extracted plots.

5.6 *Different objects*: Try to use three different objects with different masses for free fall and see how much your calculated acceleration differs in each case.

Lab I Worksheet

Name of the Student: **Date:**

Q.1 Statistics on the horizontal position

According to 5.3, you need to perform statistics on the horizontal position x vs time t for each video, and compare the standard deviation of $x(t)$ versus the criteria variation, 0.001 m. The detailed statistics should be performed in MS Excel and save the corresponding files. The final resulting statistics shall be used to fill out the following table:

Video Number	Average x (m)	Standard deviation σ_x (m)	Compare to criteria

Q.1.1 Based on the x-position statistics, do you need to redo some of the labs? If not, please go to 6.2. If yes, please redo the lab or data analysis and refill the table above.

Q.2 The plots of the vertical position (y) versus time (t)

According to 5.4, please plot all the y versus t from the 5 videos that met the criteria.

Q.2.1 Do you observe a linear or a quadratic graph?

Q.2.2 Fit all the plot with an appropriate function (Eq. 3) and determine the coefficients. Then determine the average and standard deviation of coefficients B and C.

Video Number	A (m/s^2)	B (m/s)	C (m)
Average			

Q.2.3 Based on Eq. 1, what are the physical meaning of the parameters in Q6.2.2?

Q.3 Direct vertical velocity (v_y) extraction and plots

According to 5.5, please select one video, extract v_y based on Eq. 4 using *m* = 1, 2, and 3. Plot the corresponding v_y versus *t* for all the *m*.

Q.3.1 Describe the plots of vertical velocity as a function of time. (1) Do you observe a noisy plot? (2) How does the plot change with *m*? (3) Do you observe a linear or a quadratic graph?

Q.3.2 Fit all the plots with a liner function and discuss the meaning of the fitting parameters, i.e., the slope and the intersect.

m	**Intersect (m/s)**	**Slope (m/s^2)**

Q.3.3 Compare fitting parameters of Q6.2.2 and Q6.3.2. Do you expect that some parameters in the two different data analysis to get the same values? If so, which parameters? What are the corresponding values? Are they comparable?

Q.3.4 What are the main sources of error in estimating the velocity using Eq. 4?

Q.4 Free-fall of different objects

According to 5.6, perform 5 different free fall experiments for two different objects and analyze the data according to Q.6.2. Find the acceleration and fill in the table:

Trials	a_{m1}	a_{m2}	a_{m3}
1			
2			
3			
4			
5			

Find the average of the above quantities:

	a_{m1}	a_{m2}	a_{m3}
Average			

Q.4.1 Does the acceleration depend on the type of the object?

Q.4.2 Find the percentage error of the acceleration with respect to *g*.

	m_1	m_2	m_3
Percent error			

Q.4.3 Which of these objects have an acceleration closer to *g*? Why?

Q.4.4 What are the main reasons of deviations from *g*?

Troubleshooting

Note that some errors are due to common problems in the setup. If you are calculating the acceleration to be more ± 15 % off the value of *g*, the experiment should be carefully diagnosed and done again. Here are some common problems:

- Overestimation (underestimation) of acceleration mainly is due to having the length scale being further away (closer) from the camera than the free fall motion.
- Free Fall motion should occur in 1 dimension. When you release the ball, look from the top to make sure the object is not moving away or toward the smartphone
- Length scale should be placed vertically for the free fall motion. Given that we do not have a perfectly square video recording, avoid having the length scale perpendicular to the free fall motion
- Are you confident that the camera is mounted perfectly?
    - If you notice that in the recorded video, the camera is tilted, simply rotate the coordinate system in the Tracker app
    - Please watch the instruction video or go through the phone alignment documents and double check if your smartphone is placed correctly
- Does the free-falling object look blurry in the videos? This means your recorded video was done at lower frame rate. Make sure your recordings are at 240fps.
- Error can also be due to motion tracking in the Tracker app. Please watch the instruction video for the Tracker app carefully before attempting to analyze the results

If you are still having problems in finding the acceleration accurately, please contact your TA.