Investigation of free fall using bottles of water and rocks

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Galileo Galilei proposed that, in the absence of resistance from the surrounding environment, all objects fall with the same constant acceleration regardless of mass. This indicates that constant acceleration occurs across any time interval for one object, and that the overall acceleration of one object compared to another is the same, regardless of mass. In this experiment, we tested Galileo's prediction by comparing the fall times of two identical plastic water bottles filled three-quarters of the way to the top, one with water and the other with rocks. Motion of the bottles was recorded, digitized, and analyzed. Velocity/time graphs were generated for five trials of each bottle, and acceleration was determined from the slope of the linear regression line for each trial. A two-sample unpaired *t*-test was used to compare the mean accelerations. The statistical analysis showed no significant difference between the accelerations of the two bottles, supporting Galileo's theory of free fall. Any observed variation is attributed to experimental uncertainty and timing error rather than a difference in acceleration due to mass.

I. INTRODUCTION

Galileo's claim of objects falling with the same constant acceleration independent of their mass is presented in his *Discorses on Two New Sciences* [1, 2]. This directly contradicted the Aristotelian view that a heavy body falls faster than a lighter one [3]. In Galilean free fall, acceleration is constant and uniform, and the time required for an object to fall from rest depends only on the height and gravitational acceleration, not on the object's mass.

The purpose of this experiment was to test Galileo's prediction by dropping two objects of identical shape and volume but different mass from the same height and comparing their fall times. Under Galilean assumptions, the two objects should reach the ground at the same time when dropped from the same height [4–6], demonstrating the same acceleration for objects of different masses but the same shape. The null hypothesis (H_0) states that the accelerations are equal, consistent with Galileo's theory that all objects fall with the same acceleration when resistance is neglected. Alternatively, the acclerations could differ, indicating a deviation from Galilean free fall.

$$H_0 : a_{rocks} = a_{water} \tag{1}$$

$$H_1 : a_{rocks} \neq a_{water} \tag{2}$$

II. METHODS AND MATERIALS

A. Setup

This experiment consisted of dropping two disposable 8-inch by 2.5-inch plastic water bottles (Natural Spring Water; Trader Joe's; Freehold, NJ) out of a window 5 m from the ground. One water bottle was filled with fresh

FIG. 1. (left) Bottles of rocks and water used in the experiment. (right) Drop setup from the window to the ground. This figure is not cited anywhere in the text.

tap water. The other water bottle was filled with small rocks (about 0.5 in diameter) from a suburban home garden in Manalapan, NJ. The rocks were Vigoro Bagged Marble Chip Landscape Rock (Home Depot; Marlboro, NJ). Bottles were filled with their corresponding contents to the same level (right above the label). The mass of the water bottle filled with water was 0.402 kg. The mass of the water bottle filled with rocks was 0.605 kg.

B. Drop tests

For the real-time dropping, two people were stationed on the second floor of Manalapan High School (40.2896°N, 74.3363°W) to drop the bottles. The rest of the team went to ground level to record the times it took for each bottle to fall. Walkie-talkies (UV-5R; Baofeng; Quanzhou City, China) were used to communicate. We had two digital stopwatches (Pulivia YS-802; Shenzhen, China) to time the fall, as well as a phone to back up the stopwatches. The timers were started when a countdown

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was announced from the drop team and were stopped when the ground observed the bottles landing. These values were then recorded. We used a smartphone (Samsung A21; Suwon-Si, South Korea) recording in HD at 60 fps at 1.0x zoom, placed where the ground team was standing. The video ended up being too large to upload, so we used a classmate's recording from an iPhone 11 (Apple, Inc; Cupertino, CA) at 60fps and HD. This process was repeated five times for each bottle to account for the confounding variables of the experiment, such as wind, delay from the walkie-talkies, and human error regarding starting and stopping the stopwatches. Damage to the water bottles over repeated drops was fixed by pressing the shape back into its original form.

The acceleration for each drop was calculated assuming constant, uniform acceleration:

$$a = \frac{2h}{t^2} \tag{3}$$

where $h = 5.0\,\mathrm{m}$ is the drop height and t is the measured drop time. The assumption of uniform constant acceleration was later confirmed by digitizing video, as discussed below (please see Fig. 2). Statistical analyses of the drop times and their corresponding acceleration was performed in R [7, 8].

C. Analysis

Videos were analyzed in the app FizziQ (https://www.fizziq.org/en/fizziqclassique) to obtain video kinematics [9]. As a second check of our acceleration estimates, acceleration was a;sp found from the velocity data obtained from FizziQ, which was subject to linear regression to determine the slope. Subsequent statistical analysis was performed in R [8] using the `ggplot2` and `dplyr` packages [10, 11]. All data and analysis code are available at https://github.com/devangel77b/427jkhabinskiy-lab1.

III. RESULTS

Drop times and accelerations are summarized in Table I. Differences between rocks and water are not significant for times (ANOVA, $p = 0.893$) nor for acceleration (ANOVA, $p = 0.963$).

TABLE I. Drop times and accelerations (mean $\pm$ 1 s.d.) for $n = 5$ drops. Differences between rocks and water are not significant for times (ANOVA, $p = 0.893$) nor for acceleration (ANOVA, $p = 0.963$).

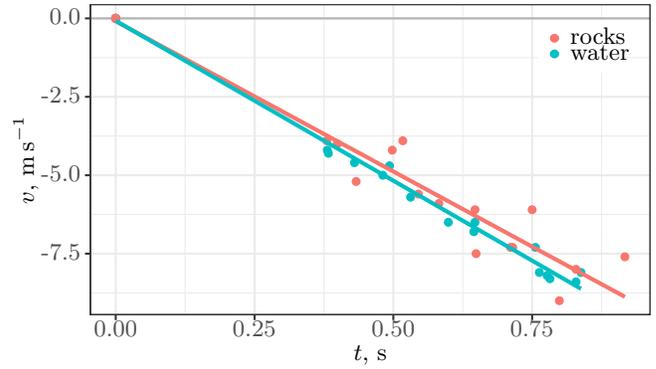|	t, s	a, m s^{-2}
rocks	0.93 ± 0.07	-12 ± 2
water	0.93 ± 0.04	-12 ± 1

FIG. 2. Velocity versus time for rocks (pink) and water (blue) including linear model fit. Acceleration values are $-10.2 \pm 0.2\,\mathrm{m\,s^{-2}}$ for water and $-9.6 \pm 0.5\,\mathrm{m\,s^{-2}}$ for rocks. The models are not significantly different (nested ANOVA, $p = 0.119$).

Velocity estimates from digitized data are shown in Fig. 2. Differences between rocks and water are not significant for times (ANOVA, $p = 0.893$) nor for acceleration (nested ANOVA, $p = 0.119$).

IV. DISCUSSION

A. Differing masses display similar accelerations, supporting Galileo

Despite a 50% greater mass for rocks versus water, both bottles fell in the same amount of time and with the same acceleration. As shown in Table I and Fig. 2, our data support Galileo's hypothesis [1, 2] and refute Aristotle's [3]. Despite differing masses, the bottles displayed very similar accelerations (Table I). The same was seen in accelerations obtained from digitized kinematics (Fig. 2): $10.2 \pm 0.2\,\mathrm{m\,s^{-2}}$ for water, and $9.6\,\mathrm{m\,s^{-2}}$ for rock. Differences between rocks and water were not significant (nested ANOVA, $p = 0.119$).

B. Sources of experimental error

Our measured accelerations (Table I) are somewhat higher than the expected value of $g = 9.8\,\mathrm{m\,s^{-2}}$. Our measured fall times are somewhat shorter than might be expected for a 5 m drop. This could be due to variation in the drop height; inadvertent slight downward velocity at release; and bias in human reaction time when timing the falls with stopwatches [12, 13]. This latter is also suggested by more reasonable estimates for g in data obtained from digitized kinematic data (Fig. 2).

V.   ACKNOWLEDGMENTS

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