Acceleration is constant during free fall

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This experiment was intended to verify the principle of constant acceleration due to gravity during a free fall. Balls of different masses, including a ping pong ball, tennis ball, cricket ball, and bowling ball, were dropped from a fixed height of 5 m. We measured the time each ball took to hit the ground, with several replicates for each type of ball. Acceleration was computed assuming it was constant over the entire fall using $a = -\frac{2h}{t^2}$. The calculated accelerations for the balls ranged from $-9.2\,\mathrm{m\,s^{-2}}$ to $-10\,\mathrm{m\,s^{-2}}$, approximately equal in magnitude to $g = 9.8\,\mathrm{m\,s^{-2}}$. Our findings support Galileo's assertion that acceleration due to gravity near the Earth's surface is constant, regardless of significant differences in mass.

I. INTRODUCTION

In physics, understanding how objects move under the influence of gravity is a fundamental concept [1–3]. Gravity is a universal force that acts on all objects with mass, causing them to accelerate toward the center of the Earth [1–3]. One of the most well-known principles of motion is that all objects fall at the same rate regardless of their mass. Galileo first proposed this idea [4, 5], contravening the prevailing Aristotelean hypothesis that heavier objects fall faster [6]. When ignoring air resistance, falling objects will accelerate due to gravity; the acceleration of gravity near the surface of the Earth is given by $g = 9.8\,\mathrm{m\,s^{-2}}$ [1–3].

We tested Galileo's hypothesis by dropping balls of different masses from a window to observe whether their acceleration differed, which would support Aristotle's alternative hypothesis, or whether the accelerations were the same, which would support Galileo. The drop tests also allowed us to independently estimate the gravitational acceleration g near the surface of the Earth. To test among the two hypotheses, we selected balls of similar size and shape, and thus similar drag, but with different masses. This allows us to examine the effect of mass without other confounding factors.

II. METHODS AND MATERIALS

A. Drop tests

As shown in Fig. 1, free-fall experiments with a variety of balls were conducted. Balls were dropped from a second floor classroom window ($h = 5$ m), with observers outside on the ground to measure the time to fall and film the resulting kinematics. Objects dropped included ping pong ball (0.0027 kg), tennis ball (0.056 kg), baseball (0.143 kg), cricket ball (0.156 kg), shotput (5.45 kg), kickball (0.210 kg), bowling ball (2.9 kg), and a big red ball (0.208 kg) to drop. For this paper, we focus on the tennis ball and cricket ball, two balls of similar size and shape, and thus similar drag, but with mass differing by a factor of three. This contrast allows testing of Galileo's versus Aristotle's hypotheses with minimal confounding effects.

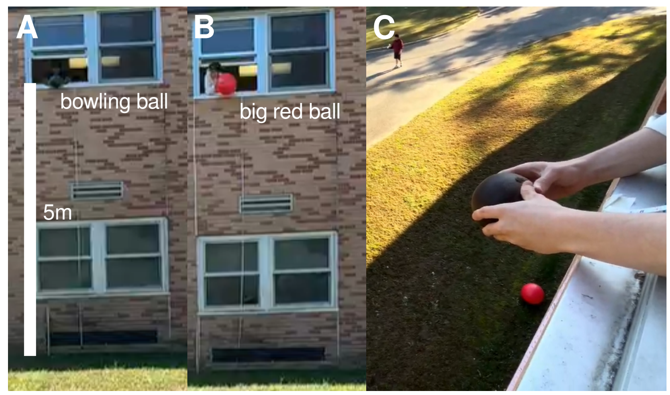

FIG. 1. Setup for drop tests. Objects were dropped from a second floor classroom window ($h = 5$ m). A. Example drop of a bowling ball. B. Example drop of a big red ball. C. View from window showing sideways grip for clean release of balls.

We recorded v from the ground using smartphones (iPhone 13; Apple, Inc; Cupertino, CA) mounted on tripods and operated at 60 frame/s. A measuring tape hung out the window and a meter stick placed at ground level provided scale references in the scene. We also measured the time it took for the ball to drop to the ground using stopwatches (Pulivia YS-802; Shenzhen, China). For each drop, balls were held out of the window for a short countdown, then cleanly released from a sideways grip, with care not to throw the ball with upward or downward velocity. The countdown also signaled observers to start the cameras and begin timing. This process was repeated five times for each object dropped and recorded. Three different people were recording the times for when the ball was dropped.

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TABLE I. Summary of measured fall time and corresponding acceleration for cricket and tennis balls.

	m, kg	t, s	a, $\mathrm{m\,s^{-2}}$
cricket	0.155	1.0 ± 0.1	10 ± 2
tennis	0.056	1.00 ± 0.04	10.0 ± 0.9

B. Analysis

Measured time data from stopwatches was used to compute acceleration, assuming the acceleration was constant and uniform. The equation for calculating the vertical position of an object undergoing uniform acceleration is [1–3]:

$$y(t) = \frac{1}{2}at^2 + v_0 t + y_0, \tag{1}$$

where v is velocity, v_0 is the inital velocity at $t = 0$, y_0 is the initial vertical position at $t = 0$, a is acceleration and t is time. Assuming the initial vertical position is $y_0 = h$, we can manipulate (1) to solve for a:

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

By convention, the acceleration of gravity is downward and $g = 9.8\,\mathrm{m\,s^{-2}}$ is tabulated as positive [1–3], so we will take the negative of (2) when tabulating our results. To indicate experimental error, times, and the resulting accelerations, are tabulated as mean ± one standard deviation. For each measured time, acceleration was calculated using (2) and $h = 5.0\,\mathrm{m}$. A two-sample t-test was then used to check for differences between cricket and tennis balls [7, 8].

For kinematic data, videos were manually digitized using Tracker [9, 10] to obtain vertical position. . Statistical analyses [7] were performed in R [8] using the `ggplot2` and `dplyr` libraries [11, 12] to obtain an additional estimate of acceleration via second-order fit of (1) to the measured position data.

All data and code are available at https://github.com/devangel77b/427rdelarosa-lab1.

III. RESULTS

Timing data are summarized in Table I and Fig. 2. For timing data and corresponding accelerations, differences between cricket and tennis balls are not significant (t-test, $t = 0.529$, $df = 5.0214$, $p = 0.6196$ for times; $t = -0.33$, $df = 5.3724$, $p = 0.75$ for acceleration).

Digitized trajectories for both cricket and tennis balls ($n = 5$ each) are given in Fig. 3. Fitting with a model of the form $y = -\frac{1}{2}gt^2 + h$ resulted in $g = (9.2 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for cricket and $g = (10.0 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for tennis (linear regression, $p < 2 \times 10^{-16}$). Differences between the two balls were significant (nested ANOVA, $p = 0.00177$).

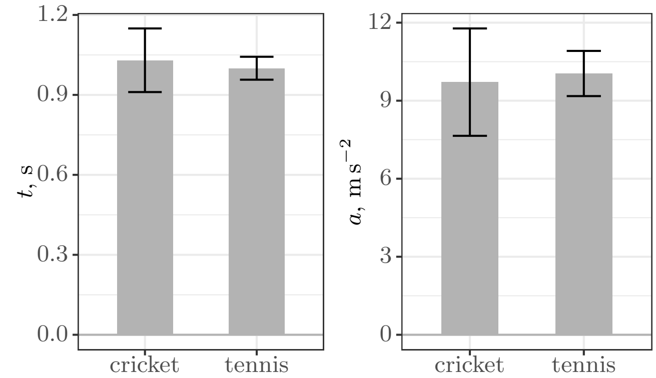

FIG. 2. Comparison of fall times (left) and acceleration (right). Differences between cricket and tennis balls are not significant (t-test, $t = 0.529$, $df = 5.0214$, $p = 0.6196$ for times; $t = -0.33$, $df = 5.3724$, $p = 0.75$ for acceleration).

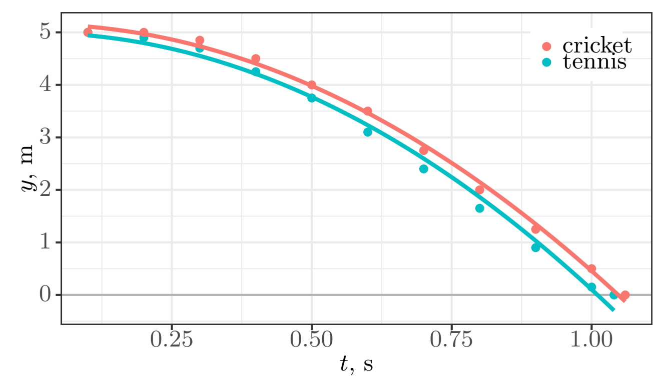

FIG. 3. Position versus time for cricket and tennis balls ($n = 5$) each. Data from manually digitized kinematics using Tracker [9]. Fitting with a model of the form $y = -\frac{1}{2}gt^2 + h$ resulted in $g = (9.2 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for cricket and $g = (10.0 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for tennis (linear regression, $p < 2 \times 10^{-16}$). Differences between the two balls were significant (nested ANOVA, $p = 0.00177$).

IV. DISCUSSION

A. Data support constant acceleration during free fall

The overall trends observed in the experiment support our hypothesis (and Galileo's) that near Earth's surface, objects fall at constant acceleration, regardless of their mass. As shown in Table I and Figs. 2 and 3, measured accelerations were close to values commonly accepted for $g = 9.8\,\mathrm{m\,s^{-2}}$ [1–3]. The good fit of a model of the form $y = -\frac{1}{2}gt^2 + h$ to the data in Fig. 3 shows the acceleration is constant during free fall. Differences between balls with a factor of three difference in mass were not significant in Table I and Fig. 2, supporting Galileo's hypothesis and refuting Aristotle's.

B. Sources of experimental error

Several sources of error may affect the results of our experiment. Human reaction time when starting and stopping the stopwatch introduced small inaccuracies in measuring the time of fall [13, 14]. We attempted to combat this by taking multiple times for different members of the grounds team. Slight inconsistencies in how each ball was released could have also influenced the drop time, hence we conducted at least five replicate drops for each ball. Variation in the outdoor conditions, such as the wind, could have also led to experimental errors. We conducted drops only when gusts were not felt.

V. ACKNOWLEDGEMENTS

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