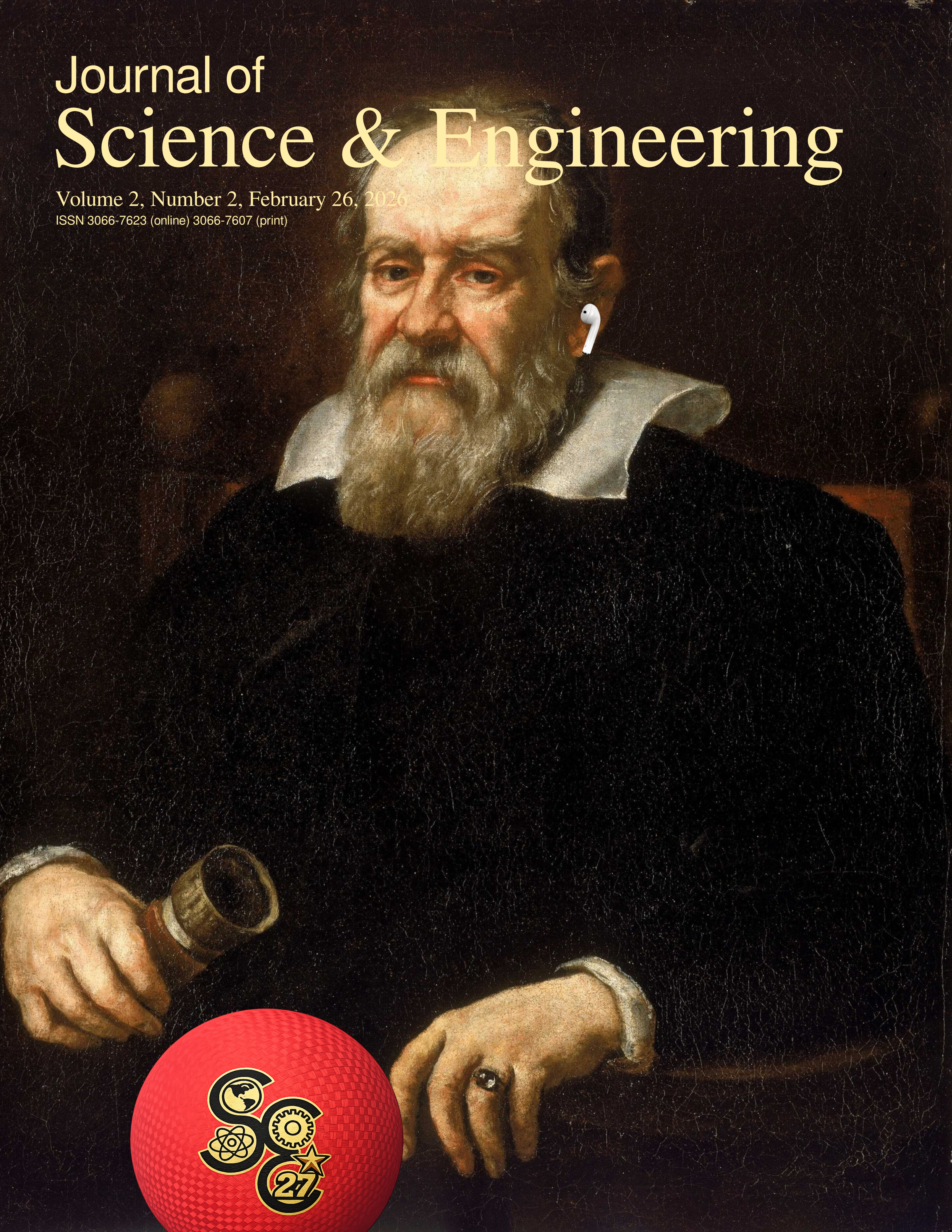
Journal of Science & Engineering

Volume 2, Number 2, February 26, 2026
ISSN 3066-7623 (online) 3066-7607 (print)



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Journal of Science & Engineering
20 Church Lane Room G201
Englishtown, NJ 07726
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Journal of
Science & Engineering

Volume 2, Number 2, February 26, 2026

From the cover: In this issue, we salute Galileo Galilei (1564-1642) who revolutionized science and developed the experimental method. We consider objects falling under the influence of gravity, as well as objects rolling on an inclined plane. We examine the kinematics of motion in these two cases, putting various hypotheses of motion to the test. ***In nullius verba,*** we will let evidence, and not authority, decide. ***Cover image:*** *Justus Sustermans, Portrait of Galileo Galilei, circa 1640, oil and wood on canvas, Royal Museums Greenwich.*

one leaf falls
alas! another
with the wind

Hattori Ransetsu, 1707

Keep track of the given
In case you
Need it for the
Equations, which
Make your life easier
And get you the answers
To your problems
In Unit 1 of AP Physics
Cause if you don't you're
Screwed.

Kelly Su

Journal of Science & Engineering **2**, 29–31 (2026)

Gravitational acceleration affects falling objects equally

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(Dated: February 26, 2026)

This experiment examines two hypotheses about the motion of falling objects: Aristotle's idea that heavier objects fall faster than lighter ones, and Galileo's idea that objects fall at a constant acceleration when air resistance is negligible. Five drop tests were conducted in which we released a kickball ($m = 0.210\,\mathrm{kg}$) and a baseball ($m = 0.144\,\mathrm{kg}$) from a height of 5 m to obtain the times it took for each object to fall a distance of 5 m. The measurements allowed us to estimate the acceleration experienced by each. Baseballs fell in $0.84 \pm 0.08\,\mathrm{s}$, while kickballs fell in $0.84 \pm 0.07\,\mathrm{s}$; the resulting accelerations were $14.7 \pm 2.8\,\mathrm{m\,s^{-2}}$ and $14.5 \pm 2.4\,\mathrm{m\,s^{-2}}$, respectively. Accelerations were approximately equal, regardless of mass; and differences between time to fall and between acceleration were not statistically significant, thus supporting Galileo's hypothesis that objects fall at a constant acceleration when air resistance is negligible.

I. INTRODUCTION

In one-dimensional kinematics, the position function $y(t)$ is a function that connects time t, acceleration a, initial velocity v_0, and initial position y_0 to produce a final position of an object[1–3]:

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

We have rewritten (1) to solve for the gravitational acceleration constant $a = -g$, assuming that the initial velocity $v_0 = 0\,\mathrm{m\,s^{-1}}$, initial position $y_0 = h$, and final position is $y = 0$ at t:

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

The importance of gravity has long been recognized in physics. The gravitational constant $g = 9.81\,\mathrm{m\,s^{-2}}$ describes the acceleration of an object falling near the Earth's surface [1–3]; but this has not always been known. In antiquity, Aristotle asserted that heavier objects fall faster than lighter objects [4], an assertion that was not challenged until Galileo Galilei, an Italian physicist, proposed that all objects fall at the same rate of acceleration when air resistance is negligible [5–7]. To test their hypotheses, we predicted that the acceleration of falling objects is constant regardless of their mass, and then conducted several drop tests using a kickball and a baseball.

The null hypothesis and alternative hypothesis are listed below:

$$H_0 : \bar{t}_k = \bar{t}_b \tag{3}$$
$$H_1 : \bar{t}_k < \bar{t}_b \tag{4}$$

where $\bar{t}_k$ and $\bar{t}_b$ denote the mean fall times of a kickball and baseball, respectively. The null hypothesis H_0 states that there is no difference in the mean fall time of the two objects, after Galileo [5, 7], while the alternative hypothesis H_1 states that the heavier object (kickball) falls faster, after Aristotle [4].

We could test among these hypotheses simply by dropping both objects and seeing which one hits the ground first. However, we chose to estimate the gravitational accelerations experienced by each as a further test. To solve for the gravitational acceleration g, we measured the fall time t and used (2). This allowed us to compare the objects' respective accelerations to see if they were equal. To verify our hypothesis, we also ran a two-sample t-test, assuming unequal variances, to further ensure its accuracy [8].

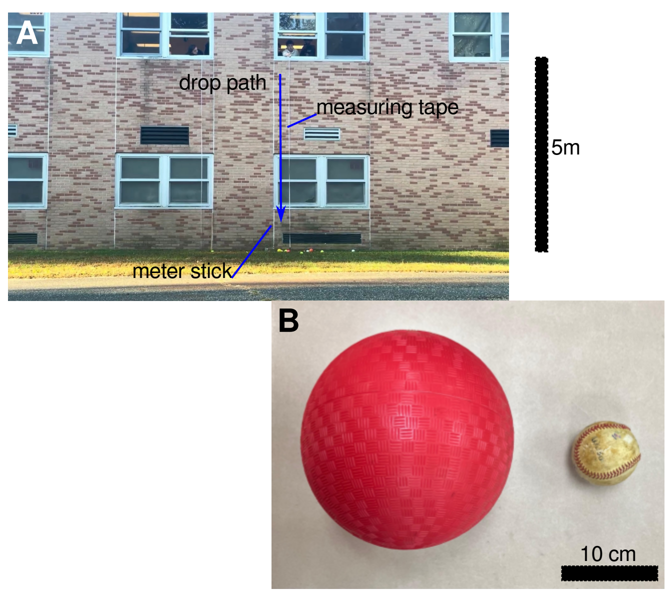

FIG. 1. A. Outdoor experimental setup depicting the drop height (5 m) used for timing falling objects. B. (left) Kickball ($m = 0.210\,\mathrm{kg}$) and (right) baseball ($m = 0.144\,\mathrm{kg}$).

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II. METHODS AND MATERIALS

A. Drop tests

In our experiment, we had one person stand inside a classroom at a second-story window, approximately 5 m above the ground, to release objects, as shown in Fig. 1A. Two of those objects were a kickball ($m = 0.210$ kg; Walmart; Freehold, NJ) with a circumference of 0.565 m and a baseball ($m = 0.144$ kg; Walmart; Freehold, NJ) with a circumference of 0.23 m, shown in Fig. 1B, which we focused on for the remainder of the experiment.

A group of observers outside at ground level measured time to fall, where each person managed one digital stopwatch (Pulivia YS-802; Shenzhen, China) with a precision of ± 0.01 s. Additional observers outside at ground level filmed each trial at 30 and 60 frame/s using a smartphone (iPhone 13; Apple Inc; Cupertino, CA).

For each trial, a sequential countdown from three down to one and a verbal command "drop" were communicated via megaphone (Pyle USA; Brooklyn, NY) to signal the person at the window to release the object from his hands by removing his hands from contact with the object or by opening his fist, depending on the size of the object. On "drop", the timers would begin their stopwatches and, through visual observation, would stop their stopwatches when the object made contact with the ground. The videographers would begin recording before the countdown and stop recording a couple of seconds after the object hits the ground. The times obtained by each stopwatch were then recorded for statistical analysis. This process was repeated over five trials, one object per trial, where each object was released from the same person's hands at the same height to maintain consistency. The experiment was conducted outdoors under calm weather conditions to minimize the effect of wind and other external factors on the objects as they fell.

B. Analysis

Statistical analysis [8] was done in R [9] using the `dplyr` and `ggplot2` packages [10, 11]. For each measured time, (2) was used to estimate g. t-tests were then performed on measured fall times as well as on the estimates of g from each drop. Data and analysis code are available at https://github.com/devangel77b/427snagrani-lab1.git

III. RESULTS

Measured fall times are shown in Table I. Table II summarizes the measured fall times and estimates of g for kickball and baseball. The data are plotted in Fig. 2. Differences are not significant between baseball and kickball (two-sample t-test, $p = 0.9269$ for t, $p = 0.8643$ for g estimates).

TABLE I. Fall times for the kickball and baseball across five trials.

trial	kickball 1, s	kickball 2, s	baseball 1, s	baseball 2, s
1	0.780	0.900	0.880	0.880
2	0.870	0.900	0.970	0.900
3	0.780	0.880	0.720	0.840
4	0.750	0.870	0.820	0.850
5	0.750	0.910	0.750	0.750

TABLE II. Fall times for kickball and baseball (mean $\pm$ 1 s.d.), for $n = 5$ drops each, and corresponding estimates of g based on (2). Differences are not significant between baseball and kickball (t-test, $p = 0.9269$ for t, $p = 0.8643$ for g estimates).

type	t, s	g, $\mathrm{m\,s^{-2}}$
baseball	0.84 ± 0.08	14.7 ± 2.8
kickball	0.84 ± 0.07	14.5 ± 2.4

IV. DISCUSSION

A. Aristotle or Galileo?

As shown in Table II and Fig. 2, the gravitational constant g_k for $n = 5$ kickballs was $14.5 \pm 2.4\,\mathrm{m\,s^{-1}}$ (mean $\pm$ 1 s.d.). The gravitational constant g_b for $n = 5$ baseballs was $14.7 \pm 2.8\,\mathrm{m\,s^{-1}}$. Both objects fell with the same acceleration (one sided, two-sample t-test, $t = 0.17343$, $df = 17.529$, $p = 0.8643$, $\alpha = 0.05$). This result is consistent with Galileo's hypothesis (H_0) that objects fall at the same rate of acceleration when air resistance is negligible [5]; and we reject Aristotle's alternative H_1, that

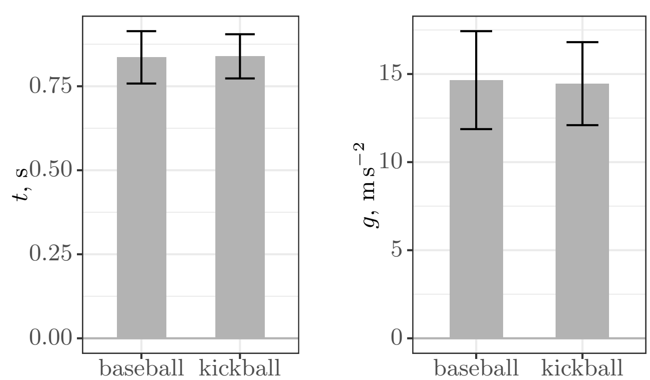

FIG. 2. (left) Bar chart of measured fall times. (right) Bar chart of g estimates. Differences are not significant between baseball and kickball (t-test, $p = 0.9269$ for t, $p = 0.8643$ for g estimates).

heavier objects fall faster.

This experiment provides experimental confirmation of Galileo's conclusion that objects of different masses fall with the same acceleration when air resistance is negligible. Although limited by human reaction time and a small sample size, our results align with the established physical theory and demonstrate the value of statistical analysis in experimental physics.

B. Sources of experimental error

Our measured values of g (Table II and Fig. 2) are somewhat higher than a typical value of $g = 9.8\,\mathrm{m\,s^{-2}}$ [1–3]. Rearranging (1) gives the time t for an object to fall distance h from rest:

$$t = \sqrt{\frac{2h}{g}}. \tag{5}$$

(5) predicts the theoretical fall time from a height of 5 m to be approximately 1.01 s. Our experimentally measured mean fall times (Tables I and II and Fig. 2) were slightly shorter than this value, which we attribute to reaction time error when using handheld stopwatches [12, 13], either due to timers starting the stopwatches late or ending them early in anticipation of objects hitting the ground. In hindsight, it may have been beneficial to have the timers give the countdown and verbal command to drop the object.

Although air resistance was neglected, it may still have had a minor effect due to differences in surface area and shape between the baseball and the kickball. Another limitation is inconsistency in drop height, which could have been reduced by providing a landmark at the window. Future experiments could improve precision by using high-speed cameras to eliminate human timing errors, having better communication among experimenters, or automating drop and timing.

V. ACKNOWLEDGMENTS

We thank our classmates who assisted with data collection and several anonymous reviewers who helped with revisions. SN collected data and documented our method and materials, results, and discussion. JB assisted in data collection, methods and materials, interpreting results, and revision of the report. KS collected visual data, described the methods and materials, interpreted results, and revised the report.

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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 *Discourses 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 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.

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.

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 ± 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, $\mathrm{m\,s^{-2}}$
rocks	0.93 ± 0.07	-12 ± 2
water	0.93 ± 0.04	-12 ± 1

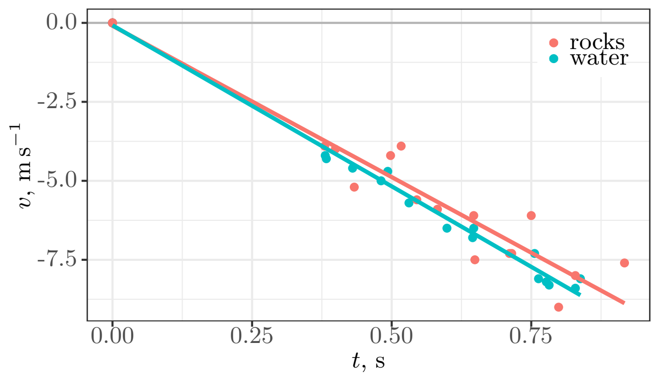

FIG. 2. Velocity versus time for rocks (pink) and water (blue) including linear model fit. Acceleration values are $-10.2 \pm 0.2\,\mathrm{m\,s^{-2}}$ for water and $-9.6 \pm 0.5\,\mathrm{m\,s^{-2}}$ for rocks. The models are not significantly different (nested ANOVA, $p = 0.119$).

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

We thank our classmates who assisted with data collection and several anonymous reviewers who helped with revisions. NB recorded the drop and completed many of the initial revisions. EP helped with timing and worked on Methods. KK helped with performing the drop, wrote part of Introduction, and did analysis. AD worked on Abstract and collected data. JK helped with timing, did the video motion analysis, Results, Discussion, and handled initial and final revisions.

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The effect of initial vertical position on velocity at which an object strikes the ground

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This experiment investigates the relationship between an object's initial vertical position and the velocity at which it strikes the ground when undergoing free fall due to gravity. For simplicity, drag was ignored. This assumption is reasonable for the cricket ball, for which drag is small compared to its weight, but may be less valid for the ping pong ball, where drag may be comparable to the gravitational force. Ping pong and cricket balls were dropped from varying heights in order to test the validity of the equation $v_f = \sqrt{2gh}$. The duration of each fall was recorded to aid in calculating experimental velocities. Results supported the theoretical relationship proposed by the equation, indicating that as height increased, final velocity increased in proportion to the square root of the height, consistent with the form of $v_f = \sqrt{2gh}$.

I. INTRODUCTION

The concept of constant acceleration in free fall dates back to Galileo, who established that objects accelerate uniformly under gravity, independent of mass [1, 2]. The kinematics equation

$$v_f^2 = v_i^2 + 2a(x - x_0) \tag{1}$$

relates an object's initial velocity v_i, final velocity v_f, acceleration a, and displacement $(x - x_0)$ and is given from the equations of motion for constant acceleration [3–6]. In free-fall, $a = g = 9.8\,\mathrm{m\,s^{-2}}$, the displacement is h, or the drop height, and $v_i = 0$ due to the object starting from rest. It follows that (1) can be rewritten as:

$$v_f^2 = 0 + 2gh. \tag{2}$$

Simplifying further, we find:

$$v_f = \sqrt{2gh}. \tag{3}$$

(3) predicts that an object's final velocity depends only on drop height and gravitational acceleration. This experiment aims to investigate the validity of this equation. Based on (3), we hypothesize that if an object is dropped from a greater initial vertical position, the object will strike the ground at a greater final velocity.

II. METHODS AND MATERIALS

A. Drop tests

This experiment was conducted using commercially available ping pong balls and cricket balls. To reduce mass-related variability, five balls of each type were measured using a CS200P scale (Ohaus Corporation; Parsippany, NJ) and were found to have consistent masses of 2.0 g (0.002 kg) for the ping pong balls and 134.6 g (0.1346 kg) for the cricket balls. Ping pong balls had a diameter of 40.0 mm (0.040 m) and cricket balls had a diameter of 72 mm (0.072 m). During the experiment, there was a gentle breeze, with an estimated wind speed of 8 mph to 12 mph ($3.6\,\mathrm{m\,s^{-1}}$ to $5.4\,\mathrm{m\,s^{-1}}$), according to AccuWeather weather reports that day. To minimize the impact of wind, only the final part of the vertical motion of the ball was analyzed.

To set up the experiment, a measuring tape was hung vertically outside a window, and a meter stick was set up to designate heights of 1 m, 2 m, and 5 m. For the test at 5 m, the meter stick was used to assist with video analysis calibration. A tripod with an iPhone 16 (Apple Inc; Cupertino, CA) was set up approximately 4.6 m from the drop site and recorded video at 240 fps with 1080p resolution and a standard wide-angle lens.

To minimize the rotation and initial push, each dropper released from rest by opening the fingers and attempting to minimize downward force and spin. For timing, stopwatches (Pulivia YS-802; Shenzhen, China) were used and began the moment the ball was dropped and stopped the moment it hit the ground. There were at least three people timing each trial. Trials that indicated significant discrepancies due to dropper variability were discarded, repeated, and new data was collected. Outliers were identified as trials where the times deviated by two or more standard deviations from the mean for a respective ball and height and were removed before averaging the data.

B. Video and statistical analyses

Video analysis was conducted using Tracker [7, 8], an open-source video kinematics tool. The calibration in Tracker was completed by using the meter stick aligned parallel to the vertical drop. The final velocity was calculated using the change in vertical position over the final five frames before impact (which helped mitigate the effects of wind).

Statistical analyses were performed in R [11] using the `dplyr` and `ggplot2` libraries [12, 13]. Data and code

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TABLE I. Measured fall times for ping pong and cricket balls at different heights. All times are given in s.

	h, m	trial 1	trial 2	trial 3	trial 4	trial 5
ping pong	1.00	0.44	0.44	0.40	0.41	0.37
ping pong	2.00	0.81	0.65	0.54	0.63	0.60
ping pong	5.00	1.25	0.97	0.91	0.91	1.09
cricket	1.00	0.38	0.43	0.47	0.44	0.45
cricket	2.00	0.51	0.54	0.57	0.65	0.51
cricket	5.00	0.75	0.87	0.90	0.82	0.84

TABLE II. Comparison of measured velocities v_m and theoretical velocities $v_f = \sqrt{2gh}$, from (3).

	h, m	t_{fall}, s	v_m, m s^{-1}	$\sqrt{2gh}$, m s^{-1}
ping pong	1.00	0.41 ± 0.03	4.04	4.43
ping pong	2.00	0.6 ± 0.1	6.33	6.26
ping pong	5.00	1.0 ± 0.1	10.05	9.90
cricket	1.00	0.43 ± 0.03	4.25	4.43
cricket	2.00	0.56 ± 0.06	5.45	6.26
cricket	5.00	0.84 ± 0.06	8.19	9.90

are provided at `https://github.com/devangel77b/427syellapragada-lab1`.

III. RESULTS

Table I provides measured drop times for all drops. Table II summarizes the drop times from Table I and compares measured velocities to theoretical predictions.

Fig. 1 shows the measured velocity as a function of drop height. For cricket, $v^2 = 13.8 \pm 0.4\,\mathrm{m\,s^{-2}}h$; while for ping pong, $v^2 = 20 \pm 1\,\mathrm{m\,s^{-2}}h$. Differences between cricket and ping pong are significant (ANOVA, $p < 2 \times 10^{-16}$).

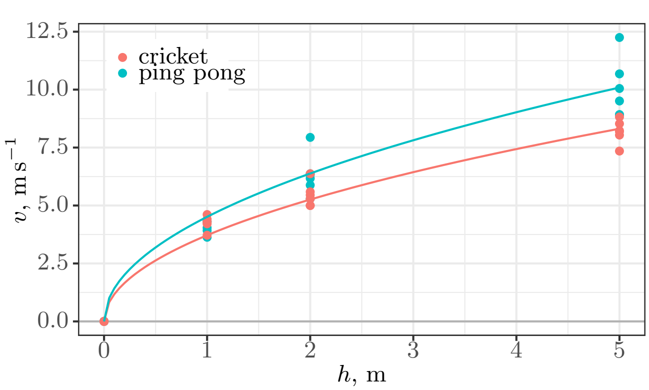

FIG. 1. Measured velocity v as a function of drop height h. For cricket, $v^2 = 13.8 \pm 0.4\,\mathrm{m\,s^{-2}}h$; while for ping pong, $v^2 = 20 \pm 1\,\mathrm{m\,s^{-2}}h$. Differences between cricket and ping pong are significant (ANOVA, $p < 2 \times 10^{-16}$).

IV. DISCUSSION

A. Does final velocity increase as initial height increases?

The results in Table II and Fig. 1 support the hypothesis that an object's final velocity increases as its initial drop height increases. Good agreement between measurement and prediction in Table II and the good fit seen in Fig. 1 also support the relationship of (3). As shown in Table I, greater drop heights correspond to longer fall times.

While final velocity does appear to increase according to $v \sim \sqrt{h}$, we were surprised to observe significant differences between cricket and ping pong balls (pink and blue lines in Fig. 1). We attempt to explain this finding below.

B. Alternate test of hypothesis using energy

An alternative way to test the hypothesis of (3) here would be to tabulate the kinetic and potential energy of an object falling or launched under the influence of gravity. This could also serve as a means to test if energy is conserved in systems undergoing translational motion.

C. Sources of experimental error

There were several possible sources of error that contributed to differences between the theoretical and experimental results. A prominent source could be air resistance, which slowed the objects slightly and prevented them from truly being in free-fall motion. However, we see higher velocities in ping pong balls compared to cricket balls (Fig. 1) and we see lower velocities in cricket balls (Table II); these are counter to what we expect for light weight, high drag ping pong balls.

Another likely source of error is human variation. Systematic errors, such as chances of improper calibration, or random errors, like human errors leading to timing inaccuracies [14, 15], variation in drop height, and changes in release technique all are possible sources of error. In an attempt to minimize this effect, we recorded at 240fps, which improved precision slightly by providing a greater number or frames and providing frames at a slower rate, however inconsistencies may have still been introduced.

V. ACKNOWLEDGEMENTS

We thank several anonymous reviewers for providing helpful comments. SD and SH primarily led on data collection as well as the writing of the introduction and methods. RW wrote the abstract and helped collect data. SY created the tables and graphs for the results, wrote

the discussion, and found scientific sources. SD completed all statistical tests and interpretations. All members contributed to proofreading and editing, as well as feedback on the paper overall.

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Journal of Science & Engineering **2**, 38–40 (2026)

Analyzing Galileo's distance-time relationship for rolling motion on an inclined plane

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(Dated: February 26, 2026)

The purpose of this experiment was to determine whether the rolling motion of spherical objects on an inclined plane is consistent with a constant-acceleration model and whether displacement is proportional to the square of time elapsed. Using a setup and procedure similar to Galileo's Renaissance-era motion on an inclined plane experiment, a ping pong ball and a baseball were rolled down a fixed inclined plane five times each, and their motion was measured using high-frame-rate video analysis. Position–time data were extracted, analyzed, and plotted to evaluate the relationship between displacement and time. Both objects exhibited displacement proportional to the square of time (t^2), indicating motion consistent with constant acceleration. These results support the application of constant-acceleration kinematics to rolling motion on an incline and are consistent with Galileo's conclusion that motion on an incline is uniformly accelerated.

I. INTRODUCTION

Uniformly accelerated motion is a fundamental concept in mechanics. For an object released from rest and undergoing constant acceleration along a straight path, displacement is related to elapsed time by:

$$x = \frac{1}{2}at^2 \tag{1}$$

where x is the displacement of the object along the incline, a is the acceleration of the object, and t is the elapsed time since the object was released from rest [1–3]. Although the equation is derived under the assumption that acceleration is constant, this relationship predicts a parabolic position–time curve and linear position-time slope, and in that sense serves as a diagnostic test for constant acceleration

This relationship was first demonstrated by Galileo Galilei in his 1638 work *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, in which he used inclined planes to study the motion of rolling objects [4, 5]. Galileo reported that, across repeated trials, "the spaces traversed were to each other as the squares of the times," independent of the inclination of the plane [4]. He further described this relationship by noting that the distances covered in successive equal time intervals follow the ratio of odd numbers: "1, 3, 5, 7..." a result which implies that total displacement grows as the square of elapsed time [4]. Galileo's inclined-plane experiments thus provided an early experimental demonstration of uniformly accelerated motion, establishing that displacement increases systematically with time rather than remaining proportional to instantaneous velocity alone.

In practical systems, rolling motion introduces rotational dynamics that fundamentally alter acceleration [1–3]. For objects rolling without slipping, translational acceleration depends on both gravitational components and the object's moment of inertia. Consequently, objects with different mass distributions or surface interactions are not necessarily expected to exhibit identical accelerations, even under similar conditions.

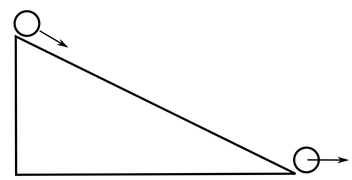

FIG. 1. General simplified overview of the schematic of our experiment

The purpose of this experiment was to recreate Galileo's inclined plane experiment, to examine whether rolling spherical objects on a fixed inclined plane exhibits displacement proportional to the square of elapsed time, consistent with constant acceleration. Using video analysis, we evaluated the extent to which constant-acceleration kinematics describes real rolling motion and identified sources of deviation from ideal behavior. Based on [4], we hypothesize that the displacement of a rolling spherical object on a fixed inclined plane is proportional to the square of elapsed time, consistent with constant acceleration over the measurement interval, e.g. (1). Alternatively, the displacement of a rolling spherical object on a fixed inclined plane does not follow a quadratic dependence on elapsed time.

II. METHODS AND MATERIALS

Two spherical objects, a ping pong ball ($m = 0.0018$ kg, diameter 40 mm) and a baseball ($m = 0.143$ kg, diameter 73 mm), were used to investigate rolling motion on an inclined plane. For rolling without slipping, each object was treated as a solid sphere with moment of inertia:

$$I = \frac{2}{5}mr^2, \tag{2}$$

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where r is the radius, reasoning for differences in measured acceleration. The inclined plane, an aluminum U-channel with an inner width of 2 cm, was elevated at a fixed 24° angle, measured with a protractor. A distance of 90 inch (2.29 m) along the incline was our measurement path. Each object was released from rest at the top of the incline without any applied push, ensuring consistent initial conditions. Rather than measure motion with chimes or pouring of wine [4], motion was recorded with an iPhone 14 camera (Apple; Cupertino, CA) at 60 frames per second with a resolution of 1080p. The camera was positioned perpendicular to the plane to best determine the position of the balls at different time intervals. Both the ping pong ball and the baseball were rolled five times under identical conditions to improve measurement reliability and reduce random error and variability.

Video analysis was performed using Tracker software [6, 7] to extract position and time data, which were plotted using Matplotlib as displacement (x) versus the square of time (t^2) based on (1). Possible sources of error, including friction, air resistance, timing precision, etc., were considered in the interpretation and analysis of results. Position data were extracted at regular time intervals using Tracker [6], with spatial calibration performed using a known reference length along the incline. Representative frames were sampled consistently every three frames across each trial to reduce noise, avoid oversampling, and balance measurement resolution.

The objects were observed to roll without sustained slipping for the majority of their motion. Any brief initial slipping immediately after release was treated as a transient effect and excluded from trend analysis. Because rolling motion couples translational and rotational dynamics, measured accelerations are expected to differ from both free-fall acceleration and frictionless sliding acceleration. No assumption was made that the accelerations of the two objects should be equal. After the constant-acceleration model was verified to be accurate, average accelerations for the baseball and the ping pong ball were measured and estimated using the relation [1–3]

$$A = \frac{2d}{t^2} \tag{3}$$

where d is the total distance traveled along the incline (90 inch, 2.29 m), and t is the time.

Results were initially visualized in Python using the `numpy`, `scipy`, and `matplotlib` libraries [8–10]. Subsequent statistical analysis [11] was perfomed in R [12] using the `ggplot2` and `dplyr` libraries [13, 14]. All data and analysis code is available at https://github.com/devangel77b/427bdemairo-lab1.

III. RESULTS

Position–time data for both the baseball and the ping pong ball were obtained from five trials each and plotted as displacement versus elapsed time. Fig. 2 shows the mean distance traveled along the incline as a function of time for all trials of the baseball and the ping pong ball, respectively. In both cases, the data exhibit a clear parabolic relationship aside from slight deviations, consistent with uniformly accelerated motion.

To further evaluate this relationship, displacement was plotted as a function of the square of time. Linear fits to these plots, as shown in Fig. 3, showed strong agreement with the constant-acceleration model of (1). This indicates that the rolling motion of both objects is well described by constant acceleration over the length of the incline. Slight discrepancies in both graphs from “perfect” parabolic or linear behavior can be attributed to previously-mentioned sources of error, ranging from the effect of rotational inertia to air resistance or precision inconsistencies.

The mean times across five trials were used to com-

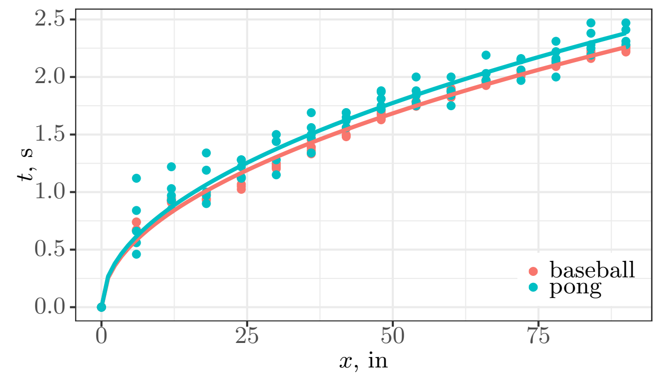

FIG. 2. Distance traveled down the inclined plane versus time for five trials for the baseball and the ping pong ball. Differences between baseball and ping pong ball are statistically significant (nested ANOVA, $p = 7.19 \times 10^{-11}$).

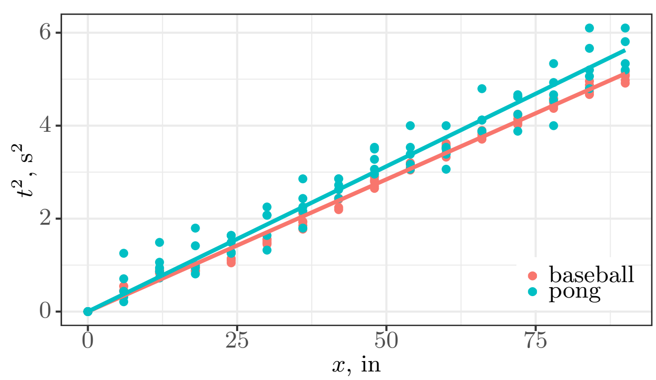

FIG. 3. Distance traveled down the inclined plane versus time squared for five trials fo the baseball and the ping pong ball. Differences between baseball and ping pong ball are statistically significant (nested ANOVA, $p = 7.19 \times 10^{-11}$).

pute representative acceleration values. For the baseball, the mean time to travel 90 in was 2.221 s, corresponding to an average acceleration of approximately $36.49\,\mathrm{in/s^2}$. For the ping pong ball, the mean time was 2.332 s, corresponding to an average acceleration of approximately $33.10\,\mathrm{in/s^2}$.

The measured accelerations, from linear regression of Fig. 3, were approximately $35.2 \pm 0.3\,\mathrm{in/s^2}$ for baseball and $32.0 \pm 0.3\,\mathrm{in/s^2}$ for ping pong. While the measured accelerations were not identical, both objects demonstrated motion consistent with constant acceleration, as evidenced by the quadratic displacement-time relationship. The observed differences in acceleration magnitude are consistent with expectations for different moments of inertia during rolling motion and do not detract from the validity of the constant-acceleration model.

IV. DISCUSSION

The results of this experiment indicate that the rolling motion of spherical objects on a fixed inclined plane is well-represented by constant acceleration. For both the baseball and the ping pong ball, displacement was appropriately found to be proportional to the square of elapsed time. This agreement supports the use of constant acceleration equations to describe rolling motion over the duration of the incline. It aligns with Galileo's original observations on the inclined plane, demonstrating uniformly accelerated motion.

Although the measured accelerations were not identical, the observed differences are expected for rolling systems and do not contradict the model of constant acceleration. Rolling motion involves rotational dynamics, causing acceleration to depend on various factors other than mass, including rotational inertia, friction, and any experimental noise. The data support the conclusion that the rolling motion of an inclined plane follows constant acceleration while highlighting the role of rotational inertia and rotational effects in real systems involving rolling and acceleration. Overall, these results do not imply identical accelerations for all rolling objects, but rather demonstrate that rolling motion can be modeled as uniformly accelerated over the experimental interval.

V. ACKNOWLEDGEMENTS

We thank the Period 1 AP Physics C Mechanics class for their assistance. We thank several anonymous reviewers for providing helpful comments on the manuscript. BD designed the experimental setup, assisted with data collection, and contributed to the historical analysis. AL assisted with experimental trials, uncertainty analysis, and contributed to data verification and figure preparation. IS conducted video analysis using Tracker, processed data in Matplotlib, and formatted the data.

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Journal of Science & Engineering **2**, 41–43 (2026)

Acceleration is constant during free fall

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(Dated: February 25, 2026)

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.

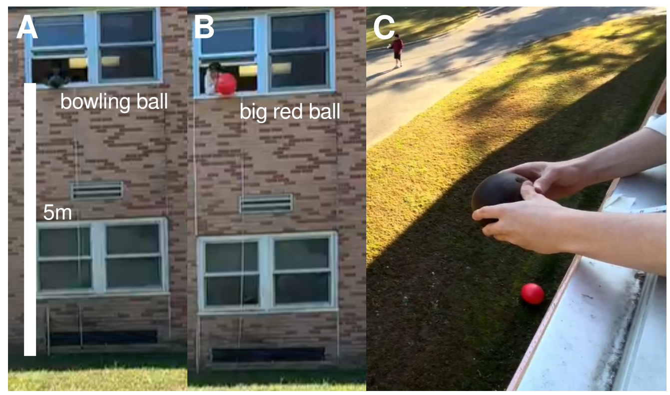

FIG. 1. Setup for drop tests. Objects were dropped from a second floor classroom window ($h = 5$ m). A. Example drop of a bowling ball. B. Example drop of a big red ball. C. View from window showing sideways grip for clean release of balls.

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, 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]:

$$y(t) = \frac{1}{2}at^2 + v_0t + y_0, \tag{1}$$

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, $p = 0.00177$).

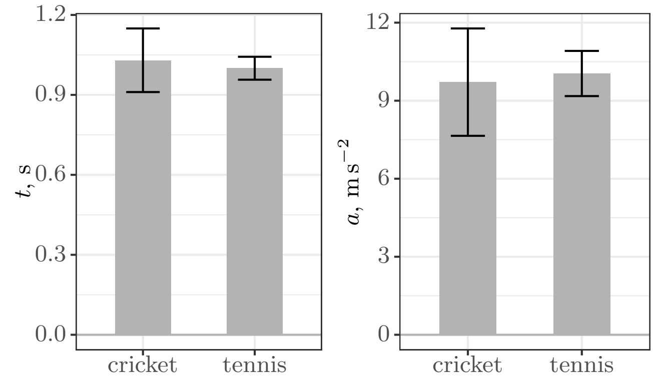

FIG. 2. Comparison of fall times (left) and acceleration (right). Differences between cricket and tennis balls are not significant (t-test, $t = 0.529$, $df = 5.0214$, $p = 0.6196$ for times; $t = -0.33$, $df = 5.3724$, $p = 0.75$ for acceleration).

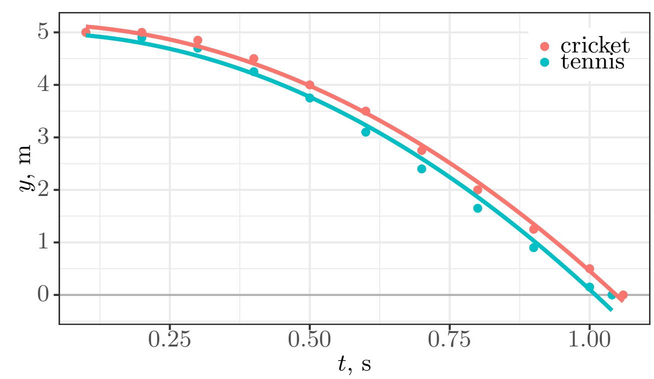

FIG. 3. Position versus time for cricket and tennis balls ($n = 5$) each. Data from manually digitized kinematics using Tracker [9]. Fitting with a model of the form $y = -\frac{1}{2}gt^2 + h$ resulted in $g = (9.2 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for cricket and $g = (10.0 \pm 0.2)\,\mathrm{m\,s^{-2}}$ for tennis (linear regression, $p < 2\times10^{-16}$). 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

We thank the Period 3 AP Physics C Mechanics class for assistance in data collection, and several anonymous reviewers for providing helpful comments. ML, DK, KC, and RD shared the work equally and declined to list individual contributions.

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Downward acceleration is independent of mass during free fall

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(Dated: February 24, 2026)

This experiment tests Galileo's theory of free fall by investigating whether or not an object's acceleration downward is dependent on its mass. Three objects of differing masses were released at rest from a height of about 5 m: a ping pong ball, a tennis ball, and a cricket ball, a mass range of three orders of magnitude. Drops were filmed and tracking software was used to record the position of each object. Position data was then used to create the graphs for velocity-time. The velocity-time graphs appeared linear with slope near $-9.8\,\mathrm{m\,s^{-2}}$, close to the accepted gravitational acceleration near Earth's surface. Since the accelerations of each object are consistent with each other to some degree of uncertainty, we conclude acceleration is independent of mass.

I. INTRODUCTION

Seeking to disprove Aristotle's idea that an object's speed in free fall is proportional to its weight [1], Galileo experimented with dropping objects from inclined planes [2, 3]. Through these experiments, he showed that in the absence of air resistance, all objects released from rest will fall at the same constant acceleration, independent of mass. Later workers showed that near Earth's surface, $g = 9.8\,\mathrm{m\,s^{-2}}$, independent of mass [4–7].

We assume the object is in free fall,that air resistance is negligible, acceleration is constant, and there is no initial velocity [5–7]. If an object is released from rest and travels vertically under these conditions, its displacement is given by

$$(x - x_0) = \frac{1}{2}gt^2. \tag{1}$$

When the initial height an object is released from is not equal to 0, the equation for position is

$$y = -\frac{1}{2}gt^2 + y_0, \tag{2}$$

where y_0 is the initial height of the object in meters and $g = 9.8\,\mathrm{m\,s^{-2}}$, and y is the vertical position of the object after time t, in seconds. Under the aforementioned conditions, motion is vertical, so we use the relevant kinematics equations to model our situation.

Under realistic conditions, however, air resistance may cause objects to accelerate at a rate slightly different from g, mainly for objects with a low mass and large surface area. We seek to examine whether these deviations in acceleration are within uncertainty of $g = 9.8\,\mathrm{m\,s^{-2}}$ by comparing the motion of three balls of different masses.

The null hypothesis for this experiment is that all objects will experience the same downward acceleration regardless of mass, while the alternative hypothesis is that one or more objects will experience a measurably different downward acceleration.

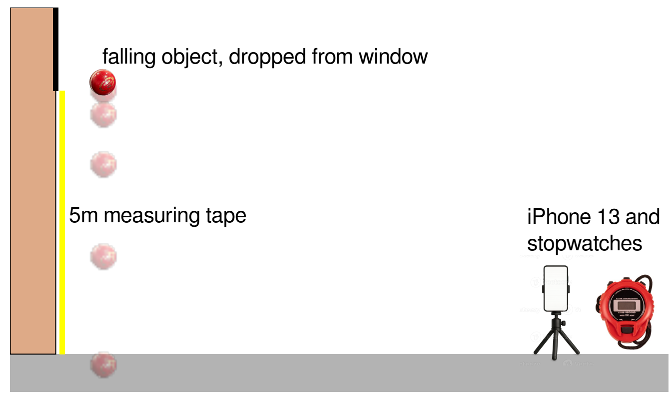

FIG. 1. Diagram of experiment setup

II. METHODS AND MATERIALS

A. Drop tests

Drop tests were conducted using the setup shown schematically in Fig. 1. To investigate the validity of Galileo's free fall theory, we used a balance to measure the mass of three different balls: a 0.002 55 kg ping pong ball, a 0.0570 kg tennis ball, and a 0.159 kg cricket ball. After, we set out a measuring tape from the second story classroom window (40.2886°N 74.3363°W) to the ground, which stretched 5 m. Away from the window, on the ground, an iPhone 13 (Apple Inc; Cupertino, CA) was mounted onto a stationary tripod approximately 20 m away, so that it is parallel to the wall of the building. This minimized error that may arise from parallax. We recorded footage at 60 frame/s. This allowed us to measure the position of the objects more frequently. As the camera captured the fall of each ball, two students were instructed to begin timing with a stopwatch (Pulivia YS-802; Shenzhen, China) as soon as the object was released, and stop when it hit the ground.

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TABLE I. Three-trial mean position y for each object. All positions given in m

t, s	cricket	pong	tennis
0.00	4.98	5.01	5.02
0.20	4.74	4.78	4.82
0.40	4.11	4.17	4.24
0.60	3.09	3.19	3.25
0.80	1.71	1.81	1.88
1.00	0.00	0.07	0.12

TABLE II. Three-trial mean velocity-time relationship of each object. All velocities given in $\mathrm{m\,s^{-1}}$.

t, s	cricket	pong	tennis
0.20	−2.18	−2.08	−1.95
0.40	−4.13	−3.98	−3.93
0.60	−6.00	−5.93	−5.90
0.80	−7.73	−7.80	−7.83

B. Analysis

To improve reliability of results and account for variability in trials, we dropped three distinct balls of each type ($n = 3$) to ensure independence across each one. We used Tracker [8] [8, 9] to analyze the recordings and find the position of the object versus time for each trial of each object. Despite using a 60 frame/s recording, we chose to use 0.20 s intervals during analysis since this interval was small enough for us to see the motion of the ball, and large enough to reduce minor tracking errors between frames. For each object, we had to align each of the three trials by defining the start of the object's free fall as time $t = 0$. Due to differing release times between trials, the averaged position values represent an approximate alignment rather than exact synchronization at each time point. We will then use the central finite difference method to calculate the velocity-time data we need to create graphs of motion for each object.

Statistical analysis [10] was performed in R [11] using the `ggplot2` and `dplyr` libraries [12, 13]. Data and code are available at https://github.com/devangel77b/427tchung-lab1.

III. RESULTS

Digitized position data are shown in Table I and Fig. 2. The resulting acceleration from Fig. 2 is $a = (9.8 \pm 0.2)\,\mathrm{m\,s^{-2}}$. Velocity data obtained Tracker are given in Table II and Fig. 3.

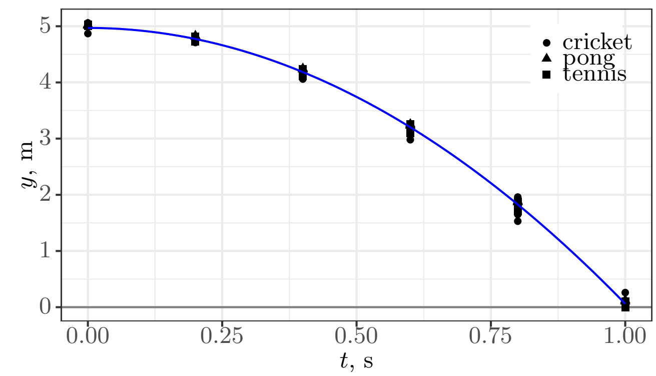

FIG. 2. Position-time data for three trials of each object ($n = 3$). There are not significant differences between the three ball types (nested ANOVA, $p = 0.06$). For these data, $y = -4.9 \pm 0.1t^2$.

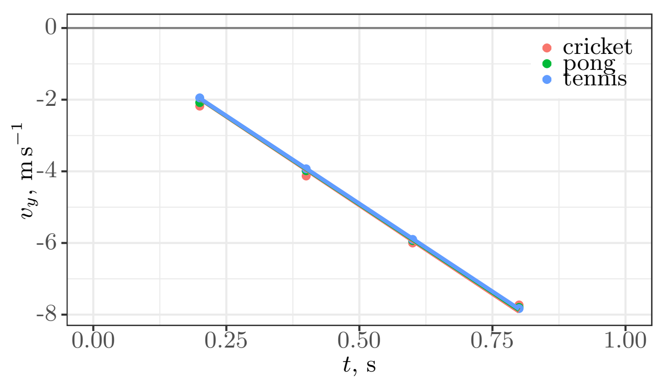

FIG. 3. Velocity-time data for three trials of each object ($n = 3$), from Table II.

IV. DISCUSSION

A. Acceleration is independent of mass

Our collected data from the three balls support Galileo's free fall theory that downward acceleration is independent of mass. As seen in Fig. 2, the position-time graph shows a parabolic curve. The velocity-time graph is linear (Fig. 3). For all points, the observed acceleration of $(-9.8 \pm 0.2)\,\mathrm{m\,s^{-2}}$ agrees well with the theoretical value of g [5–7]. Differences between balls were not significant (nested ANOVA, $p = 0.06$), supporting Galileo's hypothesis and refuting Aristotle's.

B. Sources of experimental error

Due to humans not having instant reaction speeds, the stopwatch is guaranteed to cause delays in the recording of time elapsed. In fact, manual stopwatch timing is known to introduce reaction time uncertainty of about 0.10 s [14, 15]. Additionally, it was difficult to ensure that the balls being dropped could be dropped at a constant 5 m each time. We also cannot ignore the fact that there was a fairly consistent breeze on the day in which we did our experiments, which could have influenced the motion of lighter balls like the ping pong.

V. ACKNOWLEDGEMENTS

We thank several anonymous reviewers for providing helpful comments. OA, MB, JP, and TC were responsible for data collection and setting up the experiments. OA was responsible for processing data into a readable format, TC was responsible for the initial lab write-up, JP and MB were responsible for lab revisions.

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Observations of gravitational free fall during drop experiments support a quadratic model

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When an object is dropped, standard kinematics predicts that in the absence of resistive forces, the vertical distance it travels due to gravity is described quadratically with respect to time. In this experiment, we dropped a tennis ball with negligible initial velocity from various known test heights and recorded the fall time for each trial. We then assessed whether our data were consistent with the predictions of standard kinematics, ultimately finding evidence that our height vs time data is compatible with the constant acceleration assumption of kinematics with a gravitational acceleration of magnitude $9.4 \pm 0.3\,\mathrm{m\,s^{-2}}$.

I. INTRODUCTION

Kinematics predicts that the acceleration due to gravity is a negative constant denoted by $-g$. However, since we are measuring the distance downwards, we take g to be positive [1–3].

$$a(t) = -g \tag{1}$$

Because acceleration is the instantaneous rate of change or first derivative of velocity, we can integrate over acceleration with respect to time to get an expression for velocity since derivatives and integrals are inverses by the Fundamental Theorem of Calculus [4]. Therefore, integrating both sides of (1) with respect to time, we find that the velocity as a function of time is [1–3]:

$$v(t) = -gt + v_0 \tag{2}$$

where the integration constant is interpreted as initial velocity, seeing as $v(t = 0) = v_0$. Given that velocity is the first derivative of position, we can use similar reasoning to justify integrating both sides of (2) to find:

$$y(t) = -\frac{1}{2}gt^2 + v_0 t + y_0 \tag{3}$$

where the integration constant has been interpreted as the initial position, seeing as $y(t = 0) = y_0$.

These three relations describe the motion of objects moving due to gravity near the Earth's surface under the assumption of negligible air resistance and no forces other than gravity acting upon the object in free fall.

In our experiment, we drop the masses from a fixed initial position defined to be zero, with zero initial velocity. Therefore, we hypothesize that the distance travelled by the dropped masses will be described by the following special case of (3), with g to be determined:

$$y(t) = -\frac{1}{2}gt^2 \tag{4}$$

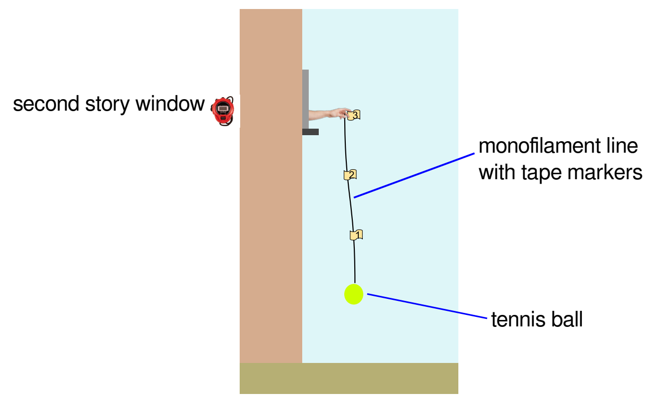

FIG. 1. Caption here

If we find that such a regression does not fit our data, then we will reject this null hypothesis, concluding that mass does not fall a distance described quadratically with respect to time as per the predictions of kinematics.

II. METHODS AND MATERIALS

A. String test apparatus

In our experiment, we utilized 5 m of monofilament fishing line with tape marking every meter, which had a tennis ball (Penn Racquet Sports; Phoenix, AZ) of mass 57.5 g hot-glued to the end and a stopwatch (Pulivia YS-802; ShenZhen YiSheng Technology Co; Shenzhen, China) to measure the time it took the ball to fall certain distances. We then took turns dropping the tennis ball out of the window while holding on to the string at the mark of how much distance we wanted the ball to fall.

B. Drop testing

Each trial began by positioning the ball at a second-story window approximately 5.0 m above the ground. Be-

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cause the maximum length of the string was equal to the 5.0 m height of the window, the string consistently caught the ball before it could make contact with the ground. The person who held this string also held a stopwatch, which they would start as soon as they dropped the ball and end when they saw and felt the ball travel the full distance. The ability of droppers to see the ball as it fell meant they could anticipate when the ball would travel the full distance, leading to both overestimates and underestimates of the fall time.

We performed this experiment with three trials per string length for seven different string lengths, meaning we conducted 21 trials in total. The string lengths were: 0.50 m, 1.00 m, 1.50 m, 2.00 m, 3.00 m, 4.00 m and 5.00 m. Initially, we only planned to use string lengths in increments of one meter, but finding ourselves with extra time on lab day, we also conducted trials for strings of length 0.5 m and 1.5 m. Distance measurements were taken with high but not perfect accuracy due to slight slippage of the tape with each trial. Timing measurements, on the other hand, were relatively volatile because of errors in human response time.

Note that we made numerous choices to reduce experimental errors in our trials. For instance, we alternated droppers so that the reflexes of those releasing the ball would not create systematic errors in our experiment. Moreover, we intentionally had droppers hold the stopwatch so that they could accurately drop the ball at the same time that they started the stopwatch.

C. Analysis

Using our experimentally determined data, we plotted distance vs time squared, in order to linearize our data. This resulted in a graph whose slope would be equal to $g/2$, based on (4).

Statistical analyses [5] were performed in R [6] using the `dplyr` and `ggplot2` packages [7, 8]. Data and code are available at `https://devangel77b/427jcardillo-lab1`.

III. RESULTS

Table I gives the measured times for each distance tested. The results are plotted in Fig. 2, which gives y as a function of t^2.

The slope of the regression line in Fig. 2 was 4.7; as a result, from (4), we estimate $g = 9.4 \pm 0.2\,\mathrm{m\,s^{-2}}$.

IV. DISCUSSION

A. Results support $y = -\frac{1}{2}gt^2$

Our results in Table I and Fig. 2 are in good agreement with (4).

TABLE I. Time to fall t, versus distance fallen y for the tennis ball

x, m		t, s	
0.50	0.32	0.34	0.37
1.00	0.56	0.50	0.56
1.50	0.50	0.56	0.47
2.00	0.70	0.67	0.63
3.00	0.81	0.75	0.78
4.00	0.95	0.90	0.85
5.00	1.02	1.07	1.02

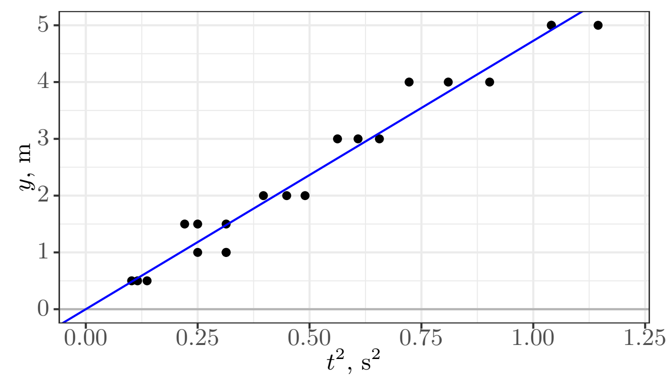

FIG. 2. Distance fallen (y) vs time squared (t^2) for the data in Table I. The slope is 4.7 ± 0.1 (linear regression, $df = 20$, $t = 44.47$, $p < 2 \times 10^{-16}$).

Also, considering the widely accepted value for the gravitational constant is $g = 9.81\,\mathrm{m\,s^{-2}}$ [1–3], our estimate of $9.4 \pm 0.2\,\mathrm{m\,s^{-2}}$ is within 5% error of the actual value, considering we had such a low-tech setup. The data also fit a model that is quadratic in time, e.g. (4), as shown in Fig. 2. These are consistent with [1, 2, 9]; objects in free fall accelerate with uniform acceleration, at least for the case of small balls falling from a second-story classroom window or some nearby Renaissance tower. Alternatives, such as linear (not accelerating) or higher order power laws were not supported.

B. Limitations and sources of experimental error

Throughout our experimentation, we experienced a few experimental errors. For instance, the tensile strength of our string was subpar and not suitable for the quantity of trials we conducted. As a result, due to the force of gravity, drops from larger heights built up greater acceleration, and therefore, a greater force was exerted upon the string, causing the string to break on one of our drops at 5 m.

However, our main setback was due to the string forming knots and tangling after each trial, due to the string bouncing as a result of its elasticity. These knots changed the length of the string and had to be manually fixed, which resulted in many retrials.

Human error was a large cause of inconsistency with our expected results in the experiment, as both starting and stopping the stopwatch off time directly impacted the data we observed [10, 11]. To remedy this, the rest of the group observed the drop, and if it appeared that the timing was incorrect, we would redo the trial.

V. ACKNOWLEDGEMENTS

We thank several anonymous reviewers for providing helpful comments. SS, JC, JC, BK, AS, and DP conducted the data collection. DP authored the Abstract, Introduction, and Discussion. BK and AS wrote the Methods and Materials. JC and JC performed the data analysis and produced the Results section.

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Testing the independence of gravitational acceleration from mass: a comparative analysis of free-falling objects near Earth's surface

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The goal of this experiment was to determine whether mass affects the acceleration during a free-fall near the Earth's surface. We dropped a 2.9 kg bowling ball and 0.142 kg baseball from a window 5.0 m off the ground; we filmed a trial for each ball and used the framerate to calculate how long it took each to hit the ground, under the specific conditions of low altitude and negligible air resistance for the dense objects. We found that both dense objects reached the ground at nearly equal times: these results support the principle, from Galileo, that mass does not affect acceleration when falling near the Earth's surface.

I. INTRODUCTION

Galileo theorized that, in the absence of air resistance, all objects fall at the same rate regardless of their mass [1, 2]. Using inclined planes, Galileo explored how objects accelerate, observing that the distance fallen increased with time squared. This also challenged the 2,000-year-old Aristotelian belief that heavier objects fall faster than lighter ones [3]. Building on Galileo's work, Sir Isaac Newton later formalized the relationship between force, mass, and acceleration in his Second Law of Motion ($\sum \vec{F} = m\vec{a}$). This law implies that the gravitational force acting on an object (its weight) is directly proportional to its mass; however, since acceleration is equal to force divided by mass, the ratio cancels out, meaning that all objects experience the same gravitational acceleration of $g = 9.8\,\mathrm{m\,s^{-2}}$, regardless of mass. The following kinematics equation shows the relation between the distance an object falls (y), the time it takes (t), and the acceleration of gravity (g) [4–6]:

$$y = -\frac{1}{2}gt^2. \tag{1}$$

In this experiment, we attempted to see if these principles held true. By comparing a baseball and a much heavier bowling ball, we wanted to observe any measurable difference in fall time (disregarding air resistance) [4–6].

II. METHODS AND MATERIALS

We collected data by dropping a bowling ball ($m = 2.9\,\mathrm{kg}$) and baseball ($m = 0.142\,\mathrm{kg}$) from a second story classroom window as shown in Fig. 1.

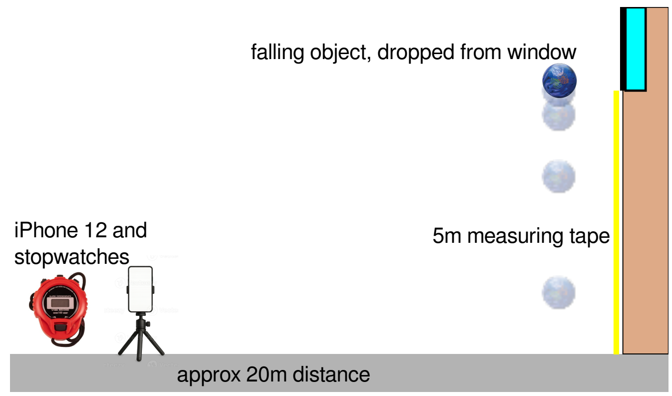

FIG. 1. Setup for drop tests of bowling balls and baseballs. Initial height was 5 m. Drops were filmed with a smartphone at approximately 20 m distance to reduce parallax.

A. Data collection

To measure the drop height y, meter sticks were secured against the exterior wall directly below the release point. Before each trial, a verbal countdown was used only to coordinate the release of the object and the start of video recording. Each drop was recorded using an iPhone 12 (Apple; Cupertino, CA) at a frame rate of 60 frame/s, allowing time measurements to be obtained from individual video frames with greater precision than a handheld stopwatch (Pulivia YS-802; Shenzhen, China). The objects were released from rest at the moment the countdown reached zero, without any initial push. The recorded videos were then analyzed using video-tracking software to digitize the trajectories and extract position–time data, from which velocities and accelerations were determined.

B. Video digitization and statistical analysis

Once all experimental trials were completed, the recorded videos were analyzed using Tracker [7, 8]. This software was used to digitize the motion of each object

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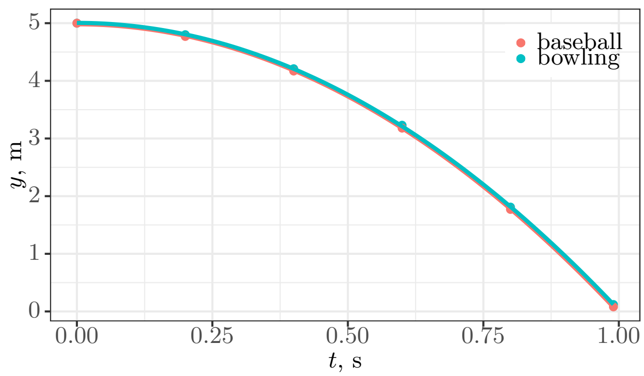

FIG. 2. Vertical position vs time

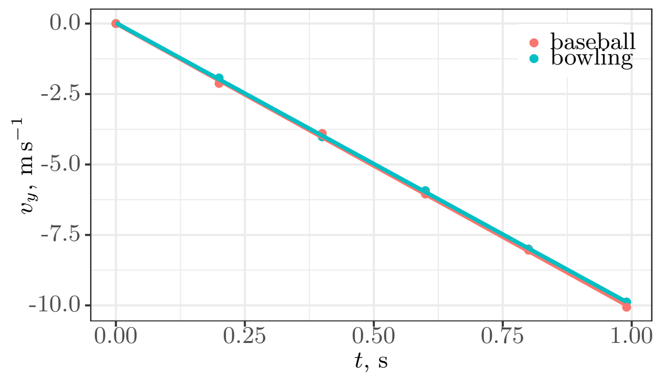

FIG. 3. Velocity vs time

frame-by-frame and extract position–time data for every trial. From these datasets, velocities and accelerations were determined through numerical differentiation and by fitting the data to constant-acceleration kinematic equations.

Acceleration is defined as the time derivative of velocity, and velocity is the time derivative of position [4–6]. For motion under constant gravitational acceleration with downward taken as the positive direction, the kinematic equations are:

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

$$v_y(t) = -gt + v_0 \tag{3}$$

$$a_y(t) = -g. \tag{4}$$

Since the objects were released from rest, the initial velocity $v_0 = 0$. Quadratic fits to the position–time data were used to determine the value of g for each trial, and the resulting accelerations were averaged across trials to obtain final values and uncertainties.

Statistical analyses [9] were performed in R [10] using the `dplyr` and `ggplot2` libraries [11, 12]. Data and code are available at https://github.com/devangel77b/4271brunie-lab1.

III. RESULTS

Fig. 2 and Table I show the vertical position data for bowling and baseball. Fig. 3 and Table II give the vertical velocity data for the same dataset. For the data shown, $g = 10.0 \pm 0.1\,\mathrm{m\,s^{-2}}$ (linear regression, $p < 2 \times 10^{-16}$). Table III summarizes the fall times for $n = 5$ drops of each ball. There are not significant differences between the two balls (t-test, $t = 0$, $df = 7.3$, $p = 1$).

TABLE I. Position of balls in m

t, s	bowling	baseball
0.00	5.00	5.00
0.20	4.80	4.77
0.40	4.21	4.17
0.60	3.23	3.18
0.80	1.81	1.77

IV. DISCUSSION

A. Objects experience the same gravitational acceleration

The results of this experiment are consistent with the prediction that objects in free fall near Earth's surface experience the same gravitational acceleration [4–6]. As shown in Fig. 2 and Fig. 3, the bowling ball (2.9 kg) and the baseball (0.142 kg) accelerate at the same rate and reach the ground together. The time to reach the ground shows no differences between balls (Table III). These support Galileo's hypothesis and refute Aristotle's.

From velocity-time data (Fig. 3), the linear relationship observed indicates that the acceleration remained approximately constant during the fall, at a value of $g = 10.0 \pm 0.1\,\mathrm{m\,s^{-2}}$. This is close to the accepted value of gravitational acceleration on Earth, $g = 9.8\,\mathrm{m\,s^{-2}}$ [4–6].

These findings support our hypothesis, originally pro-

TABLE II. Velocity of balls in $\mathrm{m\,s^{-1}}$

t, s	bowling	baseball
0.00	0.00	0.00
0.20	−1.93	−2.12
0.40	−4.02	−3.90
0.60	−5.93	−6.05
0.80	−8.00	−8.04
0.99	−9.88	−10.06

TABLE III. Summary of fall time and mass, $n = 5$ drops

	m, kg	t, s
bowling	2.9	1.00 ± 0.02
baseball	0.142	1.00 ± 0.03

posed by Galileo and later verified by Newton and others, that a free-falling object's acceleration is independent of an object's mass [1, 2]. Although the gravitational force acting on an object is proportional to its mass, as described by Newton's law of universal gravitation $F = \frac{GmM}{r^2}$, taken very near to the surface the Earth at $r = R_E$ and substituting this force into Newton's second law $F = ma$ shows that the mass of the falling object cancels and the acceleration is approximately constant, resulting in an acceleration that is independent of the object's mass [4–6].

B. Model limitations and sources of uncertainty

If the object experienced large aerodynamic forces (e.g. drag) in comparison to its weight, these results would not hold. Sources of uncertainty include air resistance and the finite frame rate of the video recording (60 frame/s), which limits timing resolution and may lead to small systematic errors in the calculated acceleration.

Additional sources of uncertainty are variations due to drop technique, systematic differences in timing with stopwatches, and camera distortion effects on digitization.

V. ACKNOWLEDGEMENTS

We thank J. Komitas and the Science and Engineering Magnet Program, for providing us with the resources and lab space to conduct our research. We thank several anonymous reviewers for providing helpful comments. LB, JK, ES, and TR avoided equally on the manuscript and declined to list individual contributions. We thank Dr Evangelista for graciously helping to format the manuscript for final publishing when we did not respond at all to any of his questions.

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Objects fall with constant acceleration regardless of mass

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This study replicated Galileo Galilei's experiment to test his hypothesis that objects fall with constant acceleration independent of mass, neglecting air resistance. We dropped five objects of varying masses (0.002 kg to 5.21 kg) from a 5 m height and measured descent times using video digitization. We compared experimental fall times to the theoretical prediction using the kinematic equation $y = -\frac{1}{2}gt^2$. Objects were found to fall with the same acceleration (ANOVA, $p = 0.34$). Linear regression analysis of distance versus t^2 yielded R^2 values between 0.92 and 0.999 across all objects, confirming that objects undergo constant acceleration. External factors such as air resistance caused minor deviations from theory, but the data strongly support Galileo's hypothesis.

I. INTRODUCTION

The Aristotelian model was scientifically dominant for approximately two thousand years, suggesting that an object's falling velocity was proportional to its weight [1]. It was not challenged for many years, until Galileo Galilei performed systematic experiments in the late sixteenth and early seventeenth centuries, which quantitatively demonstrated that all objects have a constant acceleration, and as such are affected equally in terms of gravity, when there is negligible air resistance [2, 3].

Galileo's hypothesis can be understood using the concept of gravitational acceleration; near the surface of Earth all objects have the same downward gravitation so $g = 9.8\,\mathrm{m\,s^{-2}}$. Neglecting air resistance and adopting directional convensions, the kinematic equation for distance (d), time (t) and gravitational acceleration is [4–6]:

$$d = -\frac{1}{2}gt^2 \tag{1}$$

This equation derives from calculus-based physics. Starting from the definition of acceleration as the second derivative of position with respect to time, $a = g$ (constant), we integrate twice with initial conditions of zero displacement and zero initial velocity to obtain this equation. Though calculus was not formalized during Galileo's lifetime, he arrived at equivalent relationships through geometric reasoning about instantaneous velocity and average velocity [2].

The primary hypothesis tested in this experiment is whether the relationship between fall distance and time conforms to $d = -\frac{1}{2}gt^2$ across multiple objects of different masses. If Galileo's hypothesis is correct, all objects should show the same relationship between d and t^2, regardless of mass. If Aristotle's model were correct, we would expect heavier objects to either fall faster or accelerate faster [1].

II. METHODS AND MATERIALS

A. Drop site and measurement equipment

Experiments were conducted at a second floor classroom window with a controlled outdoor drop zone. The drop height was measured using two independent methods: meter sticks positioned vertically against the exterior wall and measuring tape extended from the window to ground level. We recorded a drop height of 5.00 ± 0.05 m. The area below the drop site was cleared of obstacles and personnel before each trial.

B. Test objects

Five objects with varying masses were selected to test whether mass affects fall acceleration. The objects included a pingpong ball (2 g), a tennis ball (55 g), a large red ball (208 g), a bowling ball (6 lb, 2.72 kg), and a shotput (11.5 lb, 5.21 kg). This range of masses (spanning more than three orders of magnitude) was chosen to maximize the sensitivity of our test for mass-dependent effects on acceleration.

C. Video recording and digitization

Two iPhone 12 (Apple; Cupertino, CA) cameras were mounted on tripod stands positioned 3 m from the drop zone at perpendicular angles to ensure complete object trajectory capture. Both cameras recorded at 60 frame/s with 1080p resolution. Cameras were positioned to capture the full 5 m fall distance within the video frame and were leveled to minimize perspective distortion.

Video analysis was performed using Tracker Video Analysis and Modeling Tool (v6.1.0), open-source software designed for physics education that extracts frame-by-frame position data from video [7, 8]. The software was calibrated using the known 5 m drop height as a length reference. For each trial, the software identified the object's center in each frame and generated position-time data with an uncertainty of ± 0.05 m.

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TABLE I. Measured fall times in s for each object across $n = 5$ trials

						mean ± sd
tennis	1.01	1.03	1.00	1.02	1.01	1.01 ± 0.01
pong	1.04	1.06	1.05	1.07	1.05	1.05 ± 0.01
redball	0.99	1.00	1.01	1.00	0.99	1.00 ± 0.01
bowling	0.98	0.99	1.00	0.99	1.00	0.99 ± 0.01
shotput	0.97	0.99	1.00	0.98	0.99	0.98 ± 0.01

D. Experimental procedure

For each drop test, the test object was held stationary outside the window to ensure zero initial velocity. Cameras were started, and after 1 s of recording, the object was dropped. Each object was dropped five times, and the procedure was repeated for all five objects. A total of 25 trials were conducted over three experimental days under similar atmospheric conditions.

E. Statistical analyses

Data were visualized in Python using the `numpy`, `scipy`, and `matplotlib` libraries [9–11]. Statistical analyses [12] were performed in R [13] using the `dplyr` and `ggplot2` libraries [14, 15]. Data and code are available at https://github.com/devangel77b/427mreznik-lab1.

(1) predicts a linear relationship between distance (d) and time squared (t^2). Slopes obtained from linear regression of transformed data (d vs t^2) should give an estimate of $\frac{1}{2}g = 4.9\,\mathrm{m\,s^{-2}}$. Accordingly, plots of the data from Fig. 1, transformed in this manner, are given in Fig. 2.

III. RESULTS

Video digitization of all 25 trials yielded fall times for each object. Table I shows measured fall times from object release to ground contact. Fig. 1 shows representative trajectories for each type of ball.

Fig. 2 gives a transformation of the data in Fig. 1, plotting y versus t^2.

Table II gives the results of linear regression analysis on the transformed data (d vs t^2) shown in Fig. 2. The observed slopes ranged from $4.72\,\mathrm{m\,s^{-2}}$ to $5.31\,\mathrm{m\,s^{-2}}$, with all values bracketing the theoretical value ($4.9\,\mathrm{m\,s^{-2}}$) within measurement uncertainty.

IV. DISCUSSION

The experimental results strongly support Galileo's hypothesis that objects fall with constant acceleration independent of mass [2] and refute Aristotle [1]. Our results are valid across three orders of magnitude in mass, for

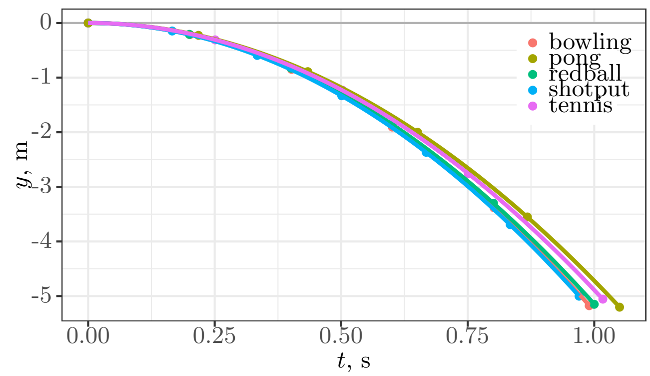

FIG. 1. Representative trajectories for each type of ball. Line is an average of the five trials for each type of ball, with trials aligned based on their start.

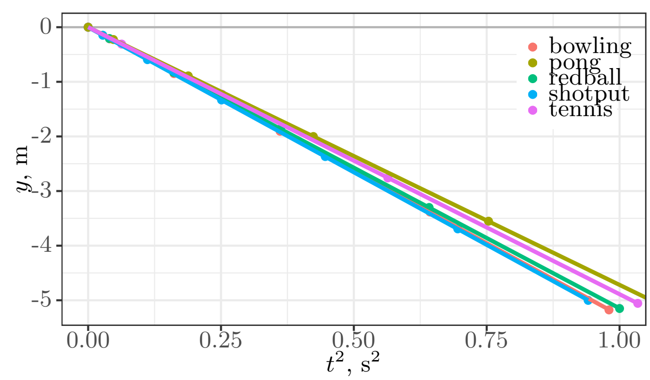

FIG. 2. Representative trajectories for each type of ball, transformed to examine y vs t^2. Each line is an average of the five trials for each type of ball, with trials aligned based on their start. Slopes are tabulated in Table II.

systems in close vicinity of the Earth's surface and in situations where air resistance and wind effects are negligible.

A. Testing Galileo's hypothesis

Galileo's hypothesis states that in the absence of air resistance, all objects fall with the same constant accel-

TABLE II. Slope obtained from digitized trajectories in $\mathrm{m\,s^{-2}}$ for $n = 5$ trials

tennis	−4.89	−5.20	−5.04	−5.15	−5.08
pong	−4.72	−5.14	−5.25	−5.24	−5.22
redball	−5.15	−5.08	−5.15	−5.14	−5.11
bowling	−5.28	−5.23	−5.17	−5.11	−5.13
shotput	−5.31	−5.26	−5.20	−5.15	−5.14

eration regardless of their mass. To test this hypothesis explicitly, we examined whether all five objects exhibit the same acceleration, as measured by the slope of the y vs t^2 regression line. As shown in Fig. 2 and Table II, the observed slopes ($4.72\,\mathrm{m\,s^{-2}}$ to $5.31\,\mathrm{m\,s^{-2}}$) are consistent with each other and with the theoretical prediction of $4.9\,\mathrm{m\,s^{-2}}$.

Additionally, an analysis of variance (ANOVA) test comparing the slopes across objects yielded $p = 0.34$, indicating no statistically significant difference in acceleration between objects of different masses. This result supports Galileo's hypothesis [2] and refute Aristotle's [1]: all objects do accelerate at approximately the same rate, regardless of mass.

B. Sources of error and deviations from theory

Several factors account for the observed deviations from the theoretical value of $4.9\,\mathrm{m\,s^{-2}}$. Small, hollow, lightweight objects with higher surface area-to-mass ratios (tennis ball, ping pong ball) showed slightly lower observed slope ($4.72\,\mathrm{m\,s^{-2}}$ to $4.89\,\mathrm{m\,s^{-2}}$), suggesting air resistance effects. Conversely, large and dense objects with lower surface area-to-mass ratios (shotput, bowling ball) showed corresponding slope values ($5.28\,\mathrm{m\,s^{-2}}$ to $5.31\,\mathrm{m\,s^{-2}}$).

The Tracker software calibration introduced a systematic uncertainty of approximately $\pm 0.05\,\mathrm{m}$ in position measurements [7, 8]. This translates to $\pm 1\%$ uncertainty in calculated acceleration values. Additionally, slight variations in timing and release technique may have imparted small initial velocities (estimated $\pm 0.02\,\mathrm{m\,s^{-1}}$), affecting measured fall times by $\pm 2\%$ [16, 17]. Light wind during some trials may have caused horizontal object displacement, introducing measurement errors in vertical position.

V. ACKNOWLEDGEMENTS

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Investigating how air resistance influences the motion of a penny and a feather

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This experiment aims to investigate the influence of air resistance on falling objects with different masses by comparing the motion at which a penny and a feather fall in environments with and without air. Creating a vacuum seal in the tube and using a high-speed video recorder, the position of each object was observed over time for five trials in each environment. In our air-filled environment, the feather fell significantly slower than the penny, almost floating downwards. On the other hand, in vacuum conditions, both objects exhibited similar position-time behavior. These results are consistent with air resistance significantly affecting the motion of low-mass, high-area objects such as feathers. In an environment without air resistance, objects experience a constant acceleration, resulting in increasing velocity over time.

I. INTRODUCTION

This experiment investigates how air resistance affects the vertical motion of a feather and a penny in a controlled tube under two conditions: with air present and with air partially removed. The motion was observed under two different conditions: We used a tube that contained air, and then the same tube, except with the air removed through a vacuum. In an idealized system without air resistance, all objects near Earth's surface accelerate at the same rate due to gravity. However, in everyday conditions, the presence of air resistance acts against the acceleration due to gravity ($9.8\,\mathrm{m\,s^{-2}}$) and reduces the net acceleration of lighter objects, particularly the feather [1–3]. By observing the feather and penny in conditions with and without air, our experiment demonstrates the influence of air resistance on objects in free fall. It provides evidence of their effects on each object's speed. We hypothesized that if objects fall in an environment with air resistance, then they will not experience constant acceleration, and may approach terminal velocity due to the opposing force of air resistance slowing down the net acceleration. However, if objects fall in an environment without air resistance, then they will accelerate uniformly due to gravity, resulting in similar accelerations due to gravity.

II. METHODS AND MATERIALS

We conducted this experiment using a meter stick, a few pieces of tape, a feather weighing 0.025 g, a penny weighing 0.050 g, a transparent acrylic tube (inner diameter 8.00 cm; Flinn Scientific; Batavia, IL), connected to a laboratory vacuum pump (JB Industries DV-85N; Aurora, IL) via a valve system to reduce air density inside the tube.

The resulting motion of objects was recorded with an smartphone (iPhone 14; Apple, Inc; Cupertino, CA) operated at 240 frame/s. The camera was mounted stationary and perpendicular to the tube to minimize perspective distortion. The high fps ensured that the objects in fall would be captured throughout, reducing human reaction error and allowing us to collect more accurate position data. To minimize other data collection errors from the video and because the tube had to be flipped, causing unsteadiness, we taped the meter stick to the tube to provide a consistent scale reference. This allowed us not to have to limit our range of motion and could flip the tube easily, all while still being able to capture a measurement of position for each of the objects in the video. To obtain the positions of each object in the presence of air resistance, the tube lid was sealed, containing both the penny and the feather, and an open valve that allowed air inside of it. Before we started to film, the tube had already been flipped upside down, and we filmed and used the data of it being flipped right side up for a total of five trials in order to average out the positions captured with the aim to minimize confounding variables that one trial may have.

To create the air-resistance-free environment, we evacuated the tube using the vacuum pump, which took around ten minutes, and then isolated the valve using two valves, one on the tube and one on the vacuum pump. Data collection proceeded as previously, for a total of five trials.

Video kinematics were digitized manually. The position of the penny and feather were recorded every 0.25 s for each trial of each object. Velocity was calculated using:

$$V_{avg} = \left|\frac{\Delta y}{\Delta t}\right| \tag{1}$$

To associate each average velocity with a time value, a midpoint time was calculated by finding the midpoint between two times, or by using the following equation:

$$t_{midpoint} = \frac{t_{next} - t_{current}}{2} \tag{2}$$

Statistical analyses [4] were conducted in R [5] using the `dplyr` and `ggplot2` libraries [6, 7]. Data and code

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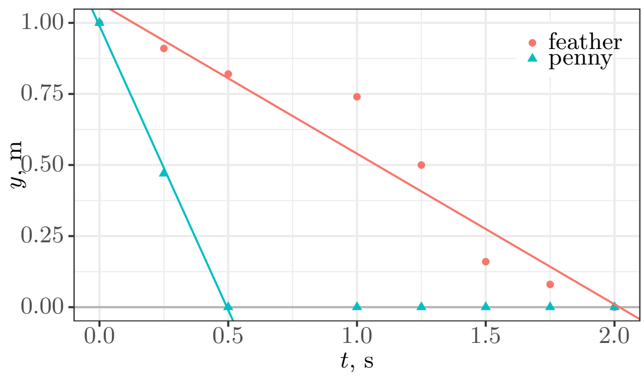

FIG. 1. Position versus time with air resistance present. For the feather, the slope is $v = -0.53 \pm 0.06\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.92$, $p = 8.49 \times 10^{-5}$). For the penny, the slope is $v = -2.00 \pm 0.07\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.997$, $p = 0.02$).

TABLE I. Midpoints of each time interval and calculated speeds ($\mathrm{m\,s^{-1}}$) for the feather across five trials, used to determine speed constancy when air resistance is present

t, s	trial 1	trial 2	trial 3	trial 4	trial 5
0.125	0.396	0.388	0.292	0.390	0.404
0.375	0.344	0.280	0.333	0.330	0.351
0.625	0.150	0.154	0.104	0.112	0.223
0.875	0.544	0.533	0.474	0.465	0.354
1.125	0.216	0.163	0.115	0.211	0.102
1.375	0.320	0.302	0.260	0.314	0.214
1.625	0.444	0.432	0.355	0.396	0.334

are available at https://github.com/devangel77b/427safzal-lab1.

III. RESULTS

Position data for the feather and penny with air resistance present are shown in Fig. 1 and Tables I and II. For the feather, the slope is $v = -0.53 \pm 0.06\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.92$, $p = 8.49 \times 10^{-5}$). For the penny, the slope is $v = -2.00 \pm 0.07\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.997$, $p = 0.02$).

Position data without air resistance are shown in Fig. 2 and Tables III and IV. There are not significant diffences between penny and feather (ANOVA, $p = 0.1388$); for the pooled data for both penny and feather, $v = -0.808 \pm 0.007\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.9992$, $p < 2 \times 10^{-16}$.

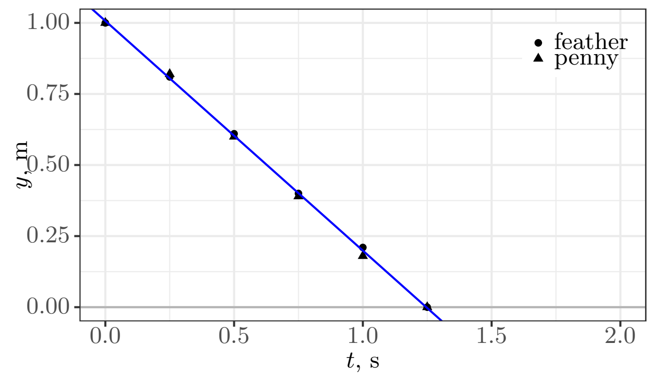

FIG. 2. Position versus time with air resistance absent. There are not significant diffences between penny and feather (ANOVA, $p = 0.1388$); for the pooled data for both penny and feather, $v = -0.808 \pm 0.007\,\mathrm{m\,s^{-1}}$ (linear regression, $R^2 = 0.9992$, $p < 2 \times 10^{-16}$.

TABLE II. Midpoints of each time interval and calculated speed ($\mathrm{m\,s^{-1}}$) for the penny across five trials, used to determine speed constancy when air resistance is present.

t, s	trial 1	trial 2	trial 3	trial4	trial 5
0.125	0.214	0.214	0.214	0.213	0.214
0.375	0.186	0.187	0.186	0.186	0.186

IV. DISCUSSION

A. With air resistance, the penny and feather fall at different velocities

Average velocities were computed over fixed intervals; this does not imply constant velocity or that terminal velocity was reached. Objects falling in air may reach a constant velocity after sufficient time due to terminal velocity; the finite tube length likely limited the extent to which full terminal velocity was reached in this experiment. Not only that, but they exhibited similar accelerations, both hitting the ground at roughly the same time. Fig. 1 displays the position of the feather and the penny in relation to time, both color-coded. The feather initially accelerated and then approached a regime where drag significantly reduced further accelera-

TABLE III. Midpoints of each time interval and calculated speeds ($\mathrm{m\,s^{-1}}$) used to determine constancy in the absence of air resistance for the feather

t, s	trial 1	trial 2	trial 3	trial 4	trial 5
0.125	0.781	0.780	0.780	0.780	0.780
0.375	0.785	0.785	0.785	0.785	0.779
0.625	0.800	0.800	0.801	0.800	0.782
0.875	0.805	0.805	0.805	0.806	0.800
1.125	0.800	0.800	0.800	0.802	0.800

TABLE IV. Midpoints of each time interval and calculated speeds ($\mathrm{m\,s^{-1}}$) used to determine constancy in the absence of air resistance for the penny

t, s	trial 1	trial 2	trial 3	trial 4	trial 5
0.125	0.800	0.800	0.801	0.800	0.800
0.375	0.811	0.812	0.811	0.811	0.811
0.625	0.812	0.811	0.812	0.811	0.811
0.875	0.800	0.801	0.800	0.801	0.800
1.125	0.801	0.801	0.801	0.801	0.801

tion where drag forced a significant reduction in further acceleration, signalling that the amount of air resistance was outweighing the feather itself. On the contrary, the penny had fallen much quicker. The amount of air resistance that the object is affected by can be determined by two things: the speed of the object and the cross-sectional area of the object, or the relative magnitude of drag forces compared to gravitational force [8]. This is exemplified through the feather, as it is tiny, weighs much less than a penny, and has soft, ridge-like corners that catch even more air, allowing for more air resistance. The penny, which is made of copper, making it more dense and heavier, does not allow for much air resistance, allowing it to fall and hit the ground almost immediately. The changing velocity is shown once again in Table I, where it is suggested that the speeds of the feather and the penny are not the same or even similar. It is, however, surprising how high the R^2 of the feather in Fig. 1 is, especially since the speeds are nowhere near being the same. Either way, a linear position-time relationship would indicate constant velocity; however, accelerating motion is expected prior to reaching terminal velocity, neither did the table of speeds show that it is constant in environments involving air resistance.

B. Without air resistance, the penny and feather fall at similar velocities

In Fig. 2, the plot of the feather and the penny is not only linear to the eye, but also very close to each other in proximity, representing similar position-time behavior consistent with constant acceleration and the same rate within each object. Supporting its linearity, the R^2 values of both the feather and the penny are 0.963 and 0.982, respectively, showing great accountability by the LSRL for all values in the data set. As seen in Table II, the speeds of both objects, after being calculated, are in fact similar, and it would be reasonable to conclude that both objects experienced similar accelerations due to gravity just as should happen in an air-resistance-free environment.

C. Sources of experimental error

Several possible sources of systemic error may have contributed to vouching for or straying away from a constant speed in an air-resistance-free environment by around 5%-10%. For example, the diameter of our tube was quite small, possibly conflicting with the actual position of each object as they collided into the wall and each other. This is especially the case for the feather and may account for its high R^2 value as given in Fig. 1. As the feather hits the sides of the tube, it may seem like it is falling more slowly when it really should not. If the penny had interacted with the feather at all, it could have pushed it down with it, causing the rate to be the same for both objects in the air-resistance-free environment when it may not have been.

Possible systematic errors include friction between the objects and the tube walls, interaction between the feather and penny, and uncertainties introduced during the tube inversion. These effects may influence the measured motion and limit generalization beyond this setup.

V. ACKNOWLEDGEMENTS

We thank several anonymous reviewers for providing helpful comments. SA produced the hypothesis, collected the data, and graphed it, allowing us to accurately depict the trends on the graph. AM was in charge of flipping the tube, ensuring that the feather and coin hit the side of the tube as little as possible to minimize outside factors that might interfere with the experiment and create a more accurate representation of no air resistance. SD was responsible for recording the experiment, ensuring the frame rate was accurate and that the data could be made intelligible from the video.

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