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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.

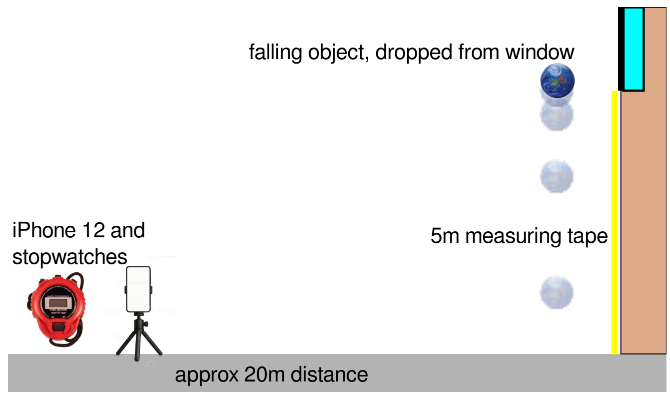

FIG. 1. Setup for drop tests of bowling balls and baseballs. Initial height was 5 m. Drops were filmed with a smartphone at approximately 20 m distance to reduce parallax.

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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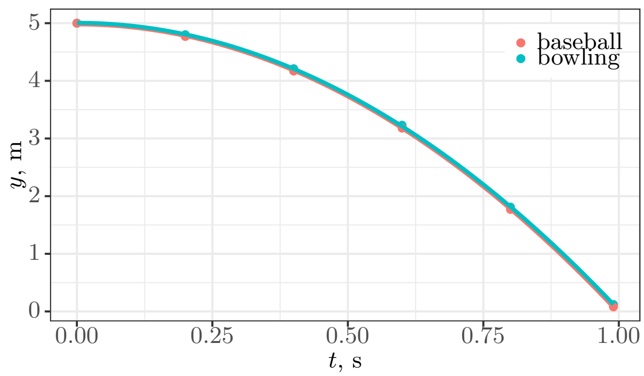

FIG. 2. Vertical position vs time

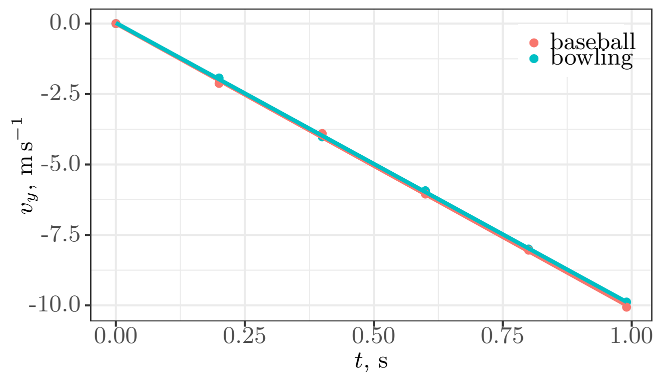

FIG. 3. Velocity vs time

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:

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

$$v_y(t) = -gt + v_0 \quad (3)$$

$$a_y(t) = -g. \quad (4)$$

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/427lbrunie-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.

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