

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

$$v_f^2 = v_i^2 + 2a(x - x_0) \quad (1)$$

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, $a = g = 9.8 \text{ m s}^{-2}$, 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:

$$v_f^2 = 0 + 2gh. \quad (2)$$

Simplifying further, we find:

$$v_f = \sqrt{2gh}. \quad (3)$$

(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 m s^{-1} to 5.4 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, $v^2 = 13.8 \pm 0.4 \text{ m s}^{-2}h$; while for ping pong, $v^2 = 20 \pm 1 \text{ m s}^{-2}h$. Differences between cricket and ping pong are significant (ANOVA, $p < 2 \times 10^{-16}$).

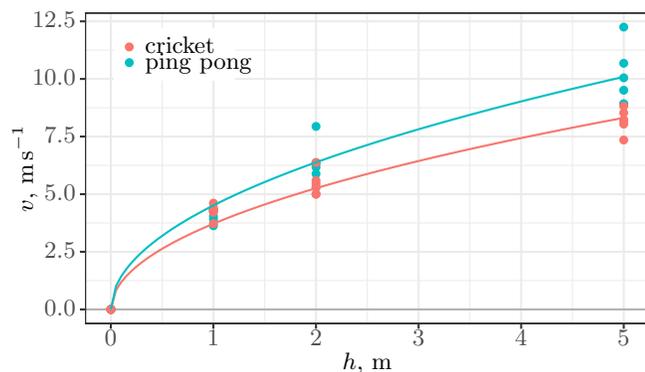


FIG. 1. Measured velocity v as a function of drop height h . For cricket, $v^2 = 13.8 \pm 0.4 \text{ m s}^{-2}h$; while for ping pong, $v^2 = 20 \pm 1 \text{ m s}^{-2}h$. Differences between cricket and ping pong are significant (ANOVA, $p < 2 \times 10^{-16}$).

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 of frames and providing frames at a slower rate, however inconsistencies may have still been introduced.

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