Investigation of energy conservation using poppers

Nimya Badmin, Kyle Koping,* and Ella Pechersky
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
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Rudolf Clausius proposed that energy cannot be created or destroyed, only transformed. This proposal is the basis of the first law of thermodynamics, the conservation of energy. This law indicates that for an object undergoing vertical motion, the initial kinetic energy is equal to the gravitational potential energy at the highest point in an ideal system. Therefore, we tested the validity of his claim. We measured a popper toy's velocity immediately after launching and at its maximum height using video digitization. We then calculated its mechanical energy to test whether energy was conserved throughout the launch. We carried out a one-sample t-test using the differences in mechanical energy to determine whether the energies at both flight points were equal. The analysis provided no statistically significant evidence that the mechanical energy of the popper was not conserved, which is consistent with Clausius' theory of conservation of energy.

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I. INTRODUCTION

The law of conservation of energy states that energy cannot be created or destroyed, but can only be transformed from one form to another, such as from potential to kinetic energy [1–4]. In an ideal system with no non-conservative forces, the mechanical energy of the system remains constant.

Potential energy is the energy stored in an object relative to its position [2–4]:

$$\mathrm{PE} = mgh. \tag{1}$$

Kinetic energy is the energy of motion [2–4]:

$$\mathrm{KE} = \frac{1}{2}mv^2. \tag{2}$$

Total mechanical energy is the sum of a system's potential and kinetic energy [2–4]:

$$\mathrm{ME} = \mathrm{PE} + \mathrm{KE}. \tag{3}$$

The purpose of this experiment was to test the principle of energy conservation by calculating and comparing the popper's total mechanical energy at launch and at its peak height.

The null hypothesis (H_0) states that the mean difference in the popper's mechanical energy at launch and at peak height is zero, meaning that the total mechanical energy remains constant and energy is conserved:

$$H_0 : E(\mathrm{ME}_f - \mathrm{ME}_0) = 0. \tag{4}$$

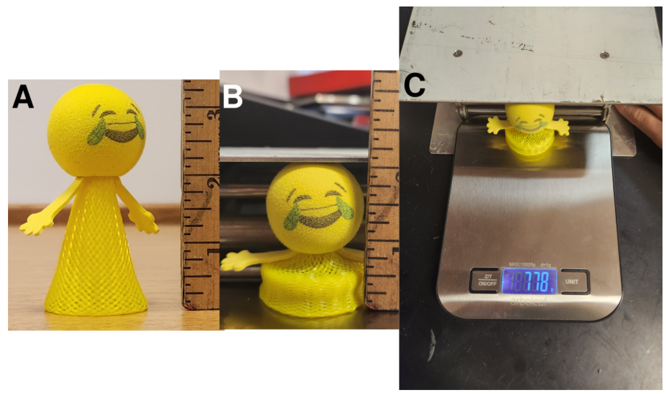

FIG. 1. (A) Uncompressed popper. (B) Compressed popper. (C) Setup for measuring mechanical work using digital scale and scissor jack.

The alternative hypothesis (H_a) states that the mean difference in the popper's kinetic energy at launch and at peak height is positive, meaning that mechanical energy is greater at launch than at peak height, indicating that some mechanical energy is lost during flight, and therefore, energy is not conserved:

$$H_a : E(\mathrm{ME}_f - \mathrm{ME}_0) > 0. \tag{5}$$

II. METHODS AND MATERIALS

A. Lab materials and setup

This experiment included the use of a popper (Jumping Emoticon Popper Spring Launchers; Liberty Imports; Allentown, PA), a scissor jack, a digital scale (TOP2KG; SmartWeight; Jiangsu, China), and a meter stick, as shown in in Fig. 1. To examine energy conservation, we launched a popper with a height of approximately 3.5-inch (89 mm; see Fig. 1A) from its maximum pos-

* Contact author: 427kkoping@frhsd.com

sible compression of approximately 2-inch (51 mm; see Fig. 1B). For digitization, a smartphone camera (iPhone 13, recording at 60fps at 1.0x zoom in HD; Apple Inc; Cupertino, CA) and video analysis software (FizziQ, version 5.0.4) were used [5, 6]. In FizziQ, digitization was performed at regular intervals (approximately every 6 frames), resulting in a total of 4-6 data points per trial, similar to [6]. A meter stick was set up vertically for scale, to measure the maximum height attained by the popper during launch. The popper was set approximately 2-inch from the yardstick so that the yardstick would not interfere with the experiment.

The mass of the popper was 6.0 g, and the force required to fully compress the popper was 778 g, which is 7.62 N. The force was found by compressing the popper with a scissor jack on a digital scale (see Fig. 1C); this method was also used to determine work done in compressing the popper, as described below.

B. Method of testing and obtaining data

For the data collection process, one person recorded the launches while another person launched the popper. The recorder was positioned so that the popper's peak height was captured on video. The recorder would begin recording and count down from five seconds before launch. The launcher would first compress the popper by pushing down on it, and then release their hand after the countdown to launch the popper into the air. This process was repeated five times to account for confounding variables, including delayed countdowns, human reaction time, and poor launching technique.

These videos were then digitized using FizziQ to find the launch velocity at the earliest possible point [5, 6]. The scale of the video was set using the meter stick as a scale reference. Then, a single point on the popper was tracked throughout its motion, with data points recorded at regular time intervals (approximately every 6 frames). These points were then used by FizziQ to generate the position and velocity data shown in the raw results.

The results from the five launches were averaged before carrying out a one-sample t-test. Calculations for the statistical test were performed using a TI-84 graphing calculator. Additional statistical analyses including ANOVA were performed in R [7–10].

To determine work done in compressing the popper, the popper was placed on the digital scale and the scissor jack was used to apply a controlled force during compression. A meter stick was placed beside the scale to measure the displacement of the popper as it was compressed. The data was recorded at multiple intervals (approximately every 0.005 m of compression), with three replicates for each compression value.

Data and analysis code are available at https://github.com/devangel77b/427kkoping-lab3.

TABLE I. Popper initial velocity, height, KE and GPE

trial	v_0, m s^{-1}	h, m	KE, J	GPE, J
1	5.29	1.43	0.0840	0.0842
2	5.27	1.45	0.0833	0.0853
3	5.06	1.33	0.0768	0.0783
4	5.50	1.67	0.0908	0.0983
5	5.68	1.54	0.0968	0.0906

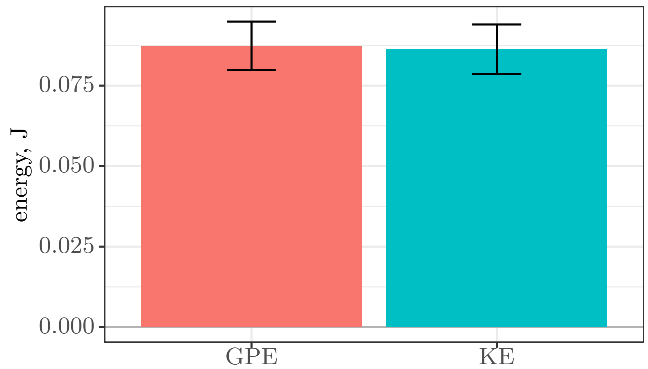

FIG. 2. Bar graph of kinetic and potential energies; data from Table I. KE and PE are not significantly different (ANOVA; $p = 0.836$).

III. RESULTS

The mass of the popper was measured to be 6.0 g (0.0060 kg). The force required to fully compress the popper was measured as 778 g force, which is equivalent to 7.62 N, using $F = mg$ where $g = 9.8\,\mathrm{m\,s^{-2}}$ [2–4].

TABLE II. Force-compression raw data for Fig. 3, to determine work to compress a popper

x, m		F, N	
0.000	0.00	0.00	0.00
0.008	1.33	1.36	0.91
0.013	2.39	2.00	1.98
0.018	2.88	2.87	3.26
0.023	3.95	3.81	3.79
0.028	5.25	5.28	5.16
0.033	6.56	6.67	6.77
0.038	7.18	7.18	7.27

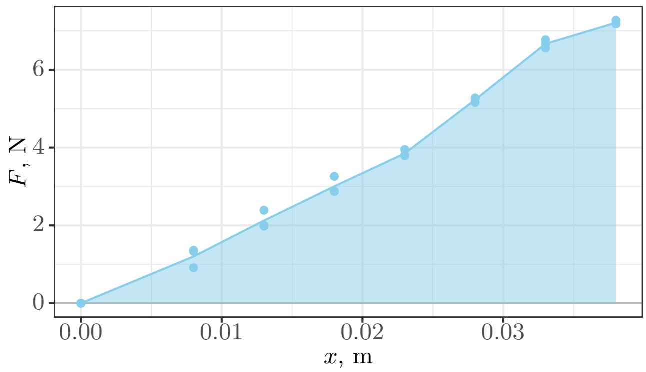

FIG. 3. Force (N) versus compression (m); data from Table II. The work done to compress the popper (shaded area) is $W = 0.130 \pm 0.001$ J.

IV. DISCUSSION

A. Energy is conserved during flight phase

Our null hypothesis (H_0) was that the mean difference in the popper's mechanical energy at launch and at peak height is zero, meaning that the total mechanical energy remains constant. Our alternative hypothesis (H_a) was that the mean difference in the popper's mechanical energy at launch and at peak height is positive, indicating that energy is lost during flight. Our results from both a one-sample t-test as well as from analysis of variance (ANOVA) fail to reject the null hypothesis and do not support the alternative hypothesis. The values of the test statistic and p-value obtained were 0.239 and 0.411, respectively, as can be seen in Table I and Fig. 2. Since the p-value is greater than the tested significance level of 0.05, there is no statistically significant difference between the mechanical energies at launch and at peak height. Therefore, there is no significant evidence to conclude that energy is lost during the popper's motion. These results are most consistent with our null hypothesis.

Although individual trials show small differences between mechanical energies at launch and at peak height, these variations are likely due to experimental error. Overall, the statistical analysis supports the idea of energy conservation. However, this result is limited by the small sample size (five replicates; one popper) and potential sources of error.

B. Energy lost during launch is significant

Kinetic energy at launch (Fig. 2) is significantly less than the work done to compress the popper (Fig. 3. With the data we obtained, we are unable to explain why the launch process loses approximately 30 % to 40 % of the elastically potential energy stored when the popper is compressed; this should be examined further in future work.

C. Sources of error

Many possible sources of error could have occurred during this experiment. For example, air resistance could cause some of the popper's mechanical energy to be lost as thermal energy and sound, resulting in slightly lower mechanical energy at peak height, although Fig. 2 shows no significant differences between KE and GPE.

Another possible source of error could be inaccuracies in digitizing the popper's motion. Camera angle distortion, limited frame rate, and human error in placing tracking points could all affect the measured position and velocity value. Additionally, variations in the popper release technique may have affected the results. Differences in how the popper was compressed and released could lead to inconsistent initial energy between trials.

V. ACKNOWLEDGEMENTS

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