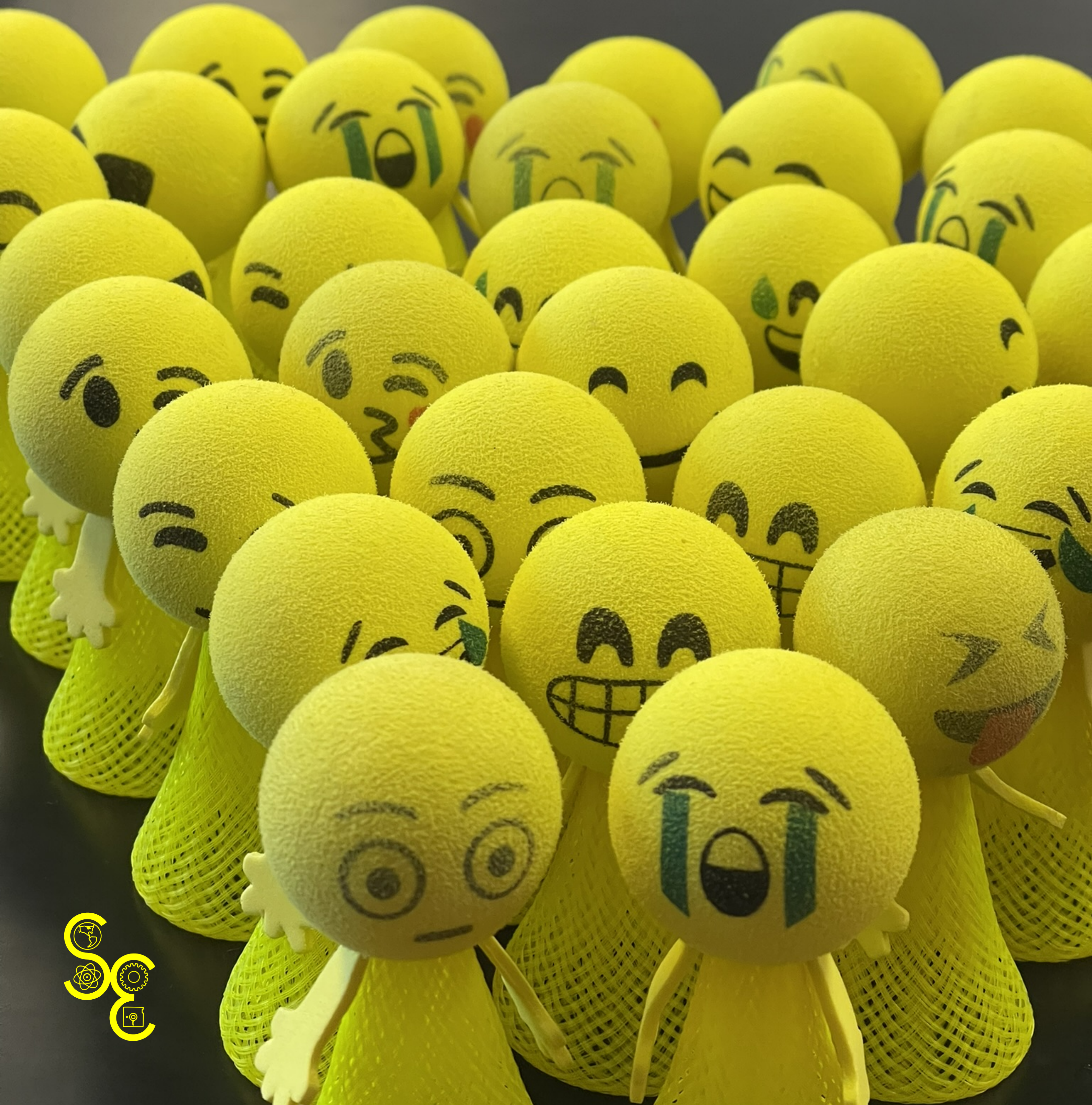
Journal of Science & Engineering

Volume 2, Number 5, May 17, 2026
ISSN 3066-7623 (online) 3066-7607 (print)



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Journal of
Science & Engineering

Volume 2, Number 5, May 17, 2026

From the cover: Energy is neither created nor destroyed, but it can change form between elastic potential energy, kinetic energy, gravitational potential energy, and heat. In this issue, we use a simple spring-loaded jumping toy to test ideas about energy conservation. *Cover image: Dennis Evangelista.*

Popper stores elastic energy
Converts into kinetic
Total stays the same

Sashank Yellapragada

Cart rolls down the ramp
Dr E tracks potential
Kinetic takes over

Ishaan Sharma

Forty MCQ
and four FRQ, you grind.
Here, now, do science!

Dennis Evangelista

Journal of Science & Engineering **2**, 83–85 (2026)

Non-conservation of mechanical energy in spring-launching toy poppers

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(Received 31 January 2026; accepted 30 March 2026; published 17 May 2026)

The law of conservation of mechanical energy states that, in an isolated system, mechanical energy remains constant as energy transforms between its kinetic and potential form without loss. This experiment investigates if energy is conserved in a 0.0055 kg spring-launching toy popper. When compressed, the toy stores elastic potential energy that is then converted to kinetic energy as the toy is released. The kinetic energy is then converted to gravitational potential energy as the toy ascends. A two-tailed paired t-test comparing the initial kinetic energy and gravitational potential energy at maximum height across ten repeated trials of the same popper yielded a statistically significant difference from zero. This result appears to suggest that mechanical energy was not fully conserved, but a more likely explanation is that we did not account for the presence of non-conservative forces such as air resistance during launch.

DOI: 10.64808/rbrn1c37

I. INTRODUCTION

The energy associated with the motion of a mass m moving at velocity v is known as kinetic energy [1–3]. This directionless, or scalar, quantity, is given by

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

The energy associated with an object's position within a conservative force field is known as its potential energy, which is given by the negative of the work exerted by the a force, or [1–3]

$$PE = -\int \vec{F} \cdot d\vec{r}. \tag{2}$$

The gravitational force exerted on objects near Earth's surface has a downward direction with a magnitude of mg, where $g = 9.8\,\mathrm{m\,s^{-2}}$ at Earth's surface [1–3]. Here, we'll assume that upward vertical displacement y is positive, so total displacement comes from initial point $y = 0$ to final position $y = h$. We use this information to calculate the gravitational potential energy of an object, given by

$$GPE = -\int_0^h (-mg)dy, \tag{3}$$

which evaluates to

$$GPE = mgh. \tag{4}$$

A system's total mechanical energy E is given by the sum of its kinetic energy and potential energy. The law of energy conservation states that this sum will remain constant unless external forces do work on the system [1–3]. Based on this law, we set up a vertical launch system where energy changes between different forms as some object rises against gravity. In this system, the initial kinetic energy of an object as it rises should be equivalent to its potential energy at the time the object reaches its maximum height and comes to a brief rest. Realistically, mechanical energy may not appear fully conserved in this system, due to losses not directly accounted for in our measurements, such as air resistance, energy dissipation into heat and sound, and inelastic behavior of the popper material [4].

To test if energy is conserved, we took ten trials of the same popper and evaluated the difference between energies in each trial. We hypothesize that either the mean difference will be zero, consistent with energy conservation (H_0); or that the mean difference will not be zero, inconsistent with energy conservation (H_a). The latter could also result from not accounting for all possible loss mechanisms in our measurements.

II. METHODS AND MATERIALS

To begin our investigation on energy conservation, we first measured the mass of a single toy popper (Liberty Imports "Jumping Gens"; Allentown, PA) to be 0.0055 kg using a balance scale (Model CK10I; Arboleaf; Plano, TX). Then, we stacked two meter sticks and pinned them against a wall as a scale reference. We also set up an iPhone 13 (Apple Inc; Cupertino, CA) parallel to the rulers to record our experimentation at 60 frame/s. We began collecting data by compressing the popper roughly 0.025 m, as further compression would result in the toy snapping through, and then releasing it. After, we replayed the video to capture the greatest height of the toy and enter it into a table. This process was repeated for ten trials to account for random variation.

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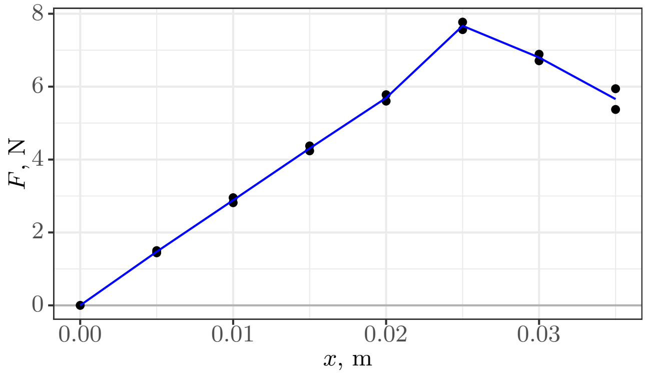

FIG. 1. F vs. x with two force data points per displacement indicating a replicate trial. Popper snap-through instability is visualized with a decrease in spring force around 0.025 m.

TABLE I. Two trials of measuring spring force (N) and displacement (m)

displacement, m	spring force, N
0	0
0.005	1.442
0.005	1.501
0.010	2.816
0.010	2.953
0.015	4.239
0.015	4.374
0.020	5.778
0.020	5.603
0.025	7.770
0.025	7.565
0.030	6.710
0.030	6.889
0.035	5.374
0.035	5.943

TABLE II. KE, PE, and the differences

trial	x, m	LKE, J	h, m	GPE, J	$LKE - GPE$, J
1	0.0254	0.0940	1.02	0.0550	0.0389
2	0.026	0.0985	1.18	0.9637	0.0348
3	0.024	0.0835	1.29	0.0696	0.0139
4	0.025	0.0909	1.13	0.0610	0.0300
5	0.027	0.106	1.32	0.0713	0.0347
6	0.026	0.0985	1.14	0.0617	0.0368
7	0.024	0.0835	1.24	0.0672	0.0163
8	0.025	0.0909	1.27	0.0685	0.0224
9	0.023	0.0764	0.91	0.0493	0.0271
10	0.026	0.0985	1.17	0.0630	0.0355

We also collected data for the force applied on the popper as its compression displacement increased. First, we placed a popper onto a balance and then compressed the popper in increments of 0.005 m, up until the displacement is 0.035 m. We chose this displacement amount since it would allow us to visualize the drop in force applied on the popper after the snap-through region of is passed. This process was repeated twice. For each trial, the mass displayed on the balance was converted to N, according to $F = mg$, and recorded.

We used (4) to calculate the gravitational potential energy at the peak height of the toy in each of our ten trials. We calculated the launch kinetic energy (LKE) across each ten trials by taking the data from our force-displacement table and creating a force-displacement function, for which we calculated the area under the curve up to the toy's snap-through region. This area is equivalent to the popper's elastic potential energy (EPE) in compression, which, in an energy-conserving system, is equal to the toy's LKE. The math can be written as the following:

$$LKE \approx EPE \approx \int_0^{\Delta x} F dx. \tag{5}$$

We evaluated the integral once for each ten trials using the displacement of compression in each using a trapezoidal sum. Finally, using the Microsoft Excel addon Analysis ToolPak, we ran a two-tailed paired t-test to determine whether or not the mean difference in energies is zero to some degree of uncertainty. Additional analyses were carried out in R [5–7]. Data and analysis code are provided at `https://github.com/devangel77b/427tchung-lab3`.

III. RESULTS

As described in section II, the area under the F vs. x curve was calculated for each compression displacement of the ten trials using a trapezoidal sum, which yielded the LKE values that were inputted into Table II.

A two-tailed paired t-test using $LKE - GPE$ values from Table II yielded a $t = 10.36$, $df = 9$, $p = 2.664 \times 10^{-6}$.

TABLE III. Mean and standard deviation of KE, PE, and LKE-GPE, $n = 10$. Data from Table II.

	mean ± 1 sd
launch kinetic energ, LKE, J	0.092 ± 0.009
max gravitational potential energy, GPE, J	0.063 ± 0.007
difference, $LKE - GPE$, J	0.029 ± 0.009

IV. DISCUSSION

A. Interpretation

The goal of this experiment was to test the law of energy conservation using a toy popper. Overall, we were unable to accurately present this law. We wrote this lab with the intention of showing that the mean difference in LKE and GPE would not significantly differ from zero, since that would be an effective representation of the law. Our statistical test, however, yielded a p-value of $p = 3 \times 10^{-6}$, a value far below any common significance level, meaning that there is a significant difference between the LKE and GPE. Since the difference between LKE and GPE was positive across each trial, we have a potential indicator that there were non-conservative forces acting on the toy which resulted in energy dissipation as it ascended. Something like air resistance may have applied negative work on the system, dissipating energy and reducing the amount that can be converted into GPE [1–3].

B. Sources of experimental error

The human eye being unable to look at two places simultaneously may have been a potential confounding variable. When recording the height of the toy, we had to look at the toy scanning for when it would approximately have zero speed in the air. We would then quickly look at the meter stick taking that height to account. This height may have been overestimated or underestimated depending on when the person watching the toy looked at the connected meter sticks on the right. We took 10 trials and averaged this out on purpose to try and avoid this, however it most likely still affected our results. Another potential source of error is ignoring air drag, which likely went against the object's motion; failure to account for this may provide an underestimate of the total energy in the system.

V. ACKNOWLEDGEMENTS

We thank the Science and Engineering faculty of Manalapan High School for providing us the means to conduct our experimental research. JP was responsible for data collection, OA wrote the abstract and interpreted the results, MB wrote the lab setup and created diagrams to represent it, TC wrote the introduction and the results of the experiment.

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Journal of Science & Engineering **2**, 86–89 (2026)

The effect of popper design on maximum jump height

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This experiment investigates whether the facial expression of a popper affects its maximum jump height using principles of energy conservation. Five "happy" poppers and five "sad" poppers were compressed to maximum depth and released, converting elastic potential energy into kinetic energy, and then gravitational potential energy. Elastic potential energy was measured via a force-compression graph ($EPE = 294.0\,\mathrm{mJ}$). Mean kinetic energy (KE) at launch was 94.1 mJ (happy) and 81.4 mJ (sad), representing approximately 32% and 28% of stored EPE respectively. Paired t-tests confirmed that KE at launch and GPE at peak were not significantly different within either group (happy: $p = 0.41$; sad: $p = 0.43$), verifying that mechanical energy is conserved during flight. Two-sample t-tests found no statistically significant difference in mass ($p = 0.12$) or height ($p = 0.24$). These results support the hypothesis that facial expression does not affect energy transfer, and that popper motion is governed by elastic properties and mass rather than surface design.

DOI: 10.64808/2t93cp73

I. INTRODUCTION

When a popper is compressed, work is done to deform the material, storing elastic potential energy (EPE). This work can be described by the area under the force versus compression graph. Upon release of the popper, EPE is rapidly converted into kinetic energy (KE), given by:

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

where m is the mass and v is the velocity [1]. As the popper rises, KE is transformed into gravitational potential energy (GPE). At maximum height (h), where velocity is approximately zero, GPE is given by:

$$GPE = mgh, \tag{2}$$

where $g = 9.8\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity [1–3].

If energy is conserved between launch and peak, as is expected from a wide body of theory [1–3], then KE will be approximately equal to GPE. In this experiment, we aim to determine whether the facial expression of a rubber popper affects its maximum jump height. Because the two designs share the same elastic properties and composition, and primarily only differ in their facial expressions, we hypothesize that facial expression will not significantly affect maximum height achieved. Additionally, we wish to find whether or not energy is conserved during the flight of the popper, acting as justification for using height as an indicator of energy transfer.

II. METHODS AND MATERIALS

This experiment was conducted using commercially available ethylene vinyl acetate (EVA) foam rubber poppers ("Jumping Gens"; Liberty Imports; Allentown, PA) with multiple emoji facial expressions. Two types were chosen: "happy," identified by an upward-curved mouth, and "sad," denoted by a downward-curved mouth and tear-like markings beneath each eye. A sample size of $n = 5$ was used for each facial expression group. The mass of each popper was measured on a digital scale (TOP2KG; Smart Weigh; Jiangsu, China).

All trials were conducted indoors on a flat, level surface within a classroom to maintain consistent environmental conditions. For measuring jump height, two meter sticks (Westcott Rule Company; Shelton, CT) were taped vertically to the wall. For each trial, to reduce experimental error, the popper was compressed to its maximum depth on the floor. Additionally, one student launched all the poppers. To ensure accuracy, the maximum height of each jump was documented on an iPhone 16 (Apple Inc; Cupertino, CA), recording at 240 fps and 1080p resolution with a standard wide-angle lens, placed at a fixed height above the ground.

Specific landmarks were used to calibrate height of the popper after launch, from which jump heights for each popper were determined and recorded using methods similar to [4]. Launch velocity was measured using FizziQ [4, 5]. The frame closest to the release of the popper was defined as $y = 0, t = 0$. To reduce bias, trial order was randomized rather than testing all poppers of one facial expression and trials in which the popper failed to launch properly were discarded. Outliers, defined as trials where the height was two or more standard deviations from the mean, were also excluded from the final analysis.

To measure EPE, a digital scale (TOP2KG; Smart Weigh; Jiangsu, China) was set to zero beneath the pop-

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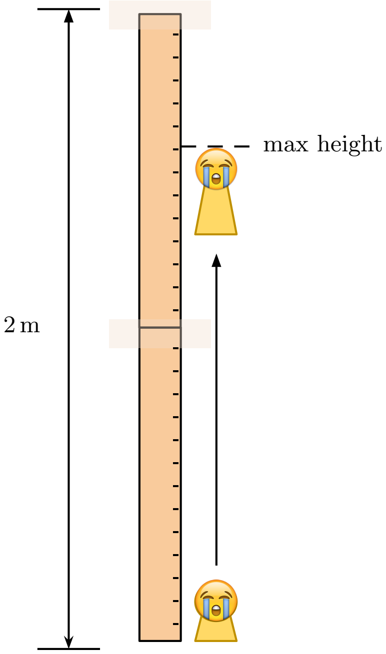

FIG. 1. Experimental setup showing the vertical calibration scale and popper placement.

per and a scissor jack was placed directly above it, compressing the popper in controlled increments. The mass readings were converted to force ($F = mg$) at each measured compression distance. EPE was calculated as the area under the force-compression curve. KE and GPE were calculated from (1) and (2) for each trial using a simple trapezoidal method [6, 7].

Data analysis and the force-compression graph were done in Google Sheets (Mountain View, CA) [8]. `R` with library `ggplot2` [7, 9, 10], was used to create a bar chart comparing the mean maximum jump height for happy and sad poppers and to perform additional statistical analyses and graphing. Data and code are provided in `https://github.com/devangel77b/427syellapragada-lab3`.

The experimental setup is illustrated in Fig. 1. The setup for measuring EPE is illustrated in Fig. 2.

III. RESULTS

The measured mass, maximum jump height, and velocity for the happy and sad popper groups are summarized in Table I and Table II, respectively.

The initial kinetic energy (KE) and maximum gravitational potential energy (GPE) for the happy and sad popper groups are summarized in Table III and Table IV, respectively.

Force-compression data are shown in Fig. 3. Total (EPE) was calculated by integrating the area under the curve in three segments, giving 294.0 mJ.

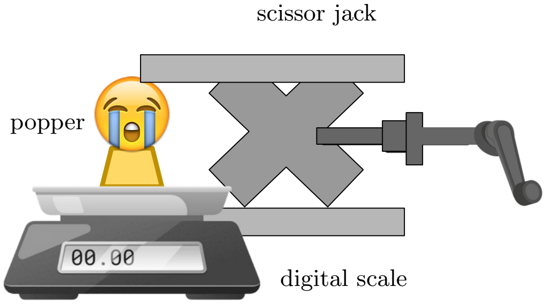

FIG. 2. The scissor jack was used to apply a controlled force and the digital scale recorded the normal force at various compressions.

TABLE I. Mass m, height h, and velocity data for happy poppers.

trial	m, kg	h, m	v_{launch}, m s^{-1}
1	0.0058	2.12	6.26
2	0.0057	1.82	6.10
3	0.0056	1.47	5.16
4	0.0057	1.67	5.78
5	0.0056	1.54	5.39
mean	0.0057	1.72	5.74
sd	0.000 08	0.26	0.46

The results of the two-sample t-tests are presented in Table V. At the $\alpha = 0.05$ significance level, no statistically significant differences were found between the two groups for either of the measured variables.

IV. DISCUSSION

The results of this experiment indicate that popper design does not have a statistically significant effect on maximum jump height. Although the mean height of the happy poppers (1.72 m) was slightly greater than that of the sad poppers (1.55 m), the distributions overlap substantially, as indicated by Fig. 4. Table V shows that $p = 0.24$ for height, which is greater than $\alpha = 0.05$.

TABLE II. Mass m, height h, and velocity data for sad poppers.

trial	m, kg	h, m	v_{launch}, m s^{-1}
1	0.0050	1.63	5.77
2	0.0055	1.30	4.90
3	0.0056	1.53	5.42
4	0.0057	1.72	5.58
5	0.0055	1.58	5.62
mean	0.0055	1.55	5.46
sd	0.0002	0.16	0.34

TABLE III. Energy data for happy poppers, based on Table I.

trial	KE, mJ	GPE, mJ	KE - GPE, mJ
1	113.6	120.6	7.0
2	105.9	101.8	4.1
3	74.4	80.8	6.3
4	95.3	93.4	1.9
5	81.3	84.6	3.4
mean	94.1	96.2	4.6
sd	16.3	15.9	2.2

TABLE IV. Energy data for sad poppers, based on Table II.

trial	KE, mJ	GPE, mJ	KE - GPE, mJ
1	83.2	80.0	3.2
2	66.0	70.1	4.1
3	82.4	84.1	1.7
4	88.6	96.2	7.5
5	87.0	85.2	1.7
mean	81.4	83.1	3.7
sd	9.0	9.4	2.4

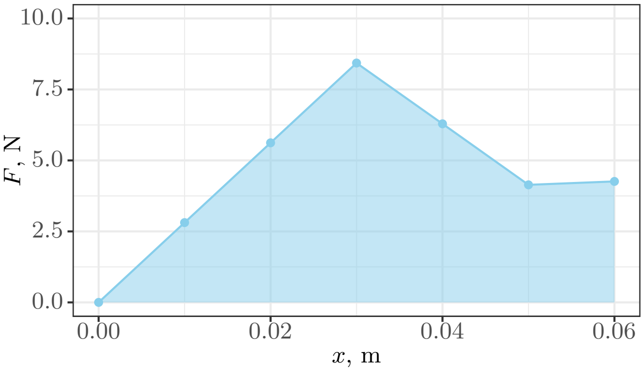

FIG. 3. Force versus compression graph used to calculate total EPE via area under the curve. The total EPE is 294 mJ.

TABLE V. Two-sample t-test results for mass m and height h; data from Tables I and II.

variable	t-value	df	p-value
mass m	1.74	8	0.12
height h	1.27	8	0.24

TABLE VI. Paired t-test results for KE at launch and GPE at peak; data from Tables III and IV.

group	t-statistic	df	p-value
happy	-0.93	4	0.41
sad	-0.88	4	0.43

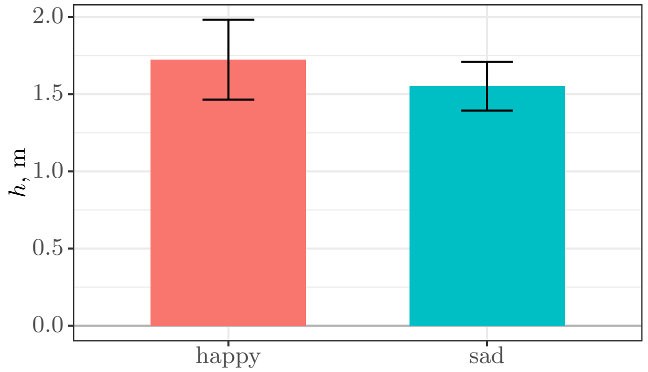

FIG. 4. Mean maximum jump height for happy and sad poppers. Error bars represent ±1 standard deviation ($n = 5$ per group).

Therefore, we fail to reject the null hypothesis. Additionally, no significant difference was found in mass ($p = 0.12$), indicating that the height difference is attributable to other factors rather than mass being a confounding variable.

Energy conservation during the flight period was tested to determine if height was a valid measure of energy output. As found in Table VI, the paired t-test within each group found no statistically significant difference between KE at launch and GPE at peak height (happy: $p = 0.41$, sad: $p = 0.43$). This confirms that mechanical energy was conserved during the flight period and that GPE at peak reliably reflects KE at launch. This also indicates that EPE was successfully transferred into upward motion.

The force-compression measurement gave an EPE of 294.0 mJ. As seen by Table I and Table II, mean KE at launch for the happy poppers was 94.1 mJ and 81.4 mJ for the sad poppers, representing approximately 32% and 28% of the stored EPE, respectively. This suggests that approximately 70% of the elastic energy is lost during the initial compression phase, likely as heat, sound, or internal deformation. Once launched, however, both types conserve energy with comparable efficiency, further supporting the conclusion that facial expression does not influence energy transfer.

Overall, the statistical results and graphical evidence support the hypothesis that facial expression does not influence maximum jump height. Instead, the motion of the poppers is governed primarily by elastic properties, mass, and energy conservation mechanisms rather than design features.

A. Sources of experimental error

A possible source of experimental error is the force at which each popper is launched. Despite the fixed location, the launch was performed by an individual rather than a repeatable machine; thus, the angle, speed, and pressure applied during compression may have varied, causing variability in the data.

Additionally, error in human reaction and observation during video analysis may have occurred [11]. Measurements taken from a meter stick in videos can be misread and are also subject to lens distortion, leading to inconsistencies [5, 12].

Finally, material wear is a likely cause of error. As the poppers had been used previously, internal deformations in the rubber may have altered the elastic properties over time, leading to inconsistent energy results [13, 14].

V. ACKNOWLEDGEMENTS

KC, SD, and SH primarily led data collection and recording. SH performed all popper compressions and authored the abstract. SY authored the introduction, methods and materials, generated the `R` code for graphical analysis, and revised the manuscript. RW calculated results based on height data. SD authored the sources of experimental error and performed all statistical analyses. KC performed the force-compression measurements, generated setup figures, and authored the discussion. All members contributed to proofreading, editing, and providing feedback on the final paper.

We thank several anonymous reviewers for comments that improved the manuscript. We acknowledge the support of the Science & Engineering program at Manalapan High School.

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Journal of Science & Engineering **2**, 90–93 (2026)

Energy is conserved in spring-like poppers

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(Received 31 January 2026; accepted 31 March 2026; published 17 May 2026)

This experiment investigates energy conservation in spring-like popper toys. A popper was compressed and released to obtain its maximum height, its velocity right after hitting the maximum height, and its velocity upon release for five trials. The kinetic energy equation and the potential energy equation were evaluated with the obtained values, where the average of the yielded kinetic energy and potential energy values, 0.068 94 J and 0.079 22 J, respectively, were compared and found to be approximately equal. The elastic potential energy stored in the popper before launch was 0.257 J, further supporting the idea that energy is conserved. A paired t-test comparing the average kinetic energy at launch and the average gravitational potential energy at maximum height for a popper for five trials yielded $p = 0.424$, revealing no statistically significant difference between the kinetic energy at launch and the potential energy at the popper's highest point. This means that the kinetic energy at launch and the potential energy at maximum height are close enough to be comparable, further supporting the idea that energy is conserved.

DOI: 10.64808/csnmd731

I. INTRODUCTION

Kinetic energy (KE) is the energy inside a moving object that makes it move, and can be calculated by the kinetic energy equation [1–3]:

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

where m is mass and v is velocity v.

Gravitational potential energy (GPE) is given by [1–3]:

$$GPE = mgh, \tag{2}$$

where m is mass, h is height above some reference height, and $g = 9.8\,\mathrm{m\,s^{-2}}$ is the acceleration of gravity.

We hypothesize that energy is conserved in a frictionless environment, meaning that the total energy of the system should remain constant. Friction was neglected to simplify the experiment, as it has no significantly large impact on the data. The kinetic energy of the system just as the popper left the ground, and the gravitational potential energy of the system at the popper's maximum height were calculated with (1) and (2), respectively, where the system consists of the popper.

The null hypothesis and alternative hypothesis are listed below:

$$H_0 : KE = GPE, \tag{3}$$
$$H_1 : KE \neq GPE. \tag{4}$$

H_0 states that energy is conserved during the popper's motion, meaning the kinetic energy at launch is equal to the gravitational potential energy at maximum height. This would imply that there is no significant difference between the kinetic energy at launch and the potential energy at the popper's maximum height. Alternatively, H_1 states that energy is not conserved during the popper's motion, meaning the kinetic energy at launch is not equal to the gravitational potential energy at maximum height.

To test our hypotheses, we captured video kinematics and analyzed them using methods similar to [4]. FizziQ [4, 5] was used to compute the popper's velocity as it left the initial position $y = 0$ for (1). The initial gravitational potential energy U_0 was defined as zero for all calculations to represent the absence of energy in the system at rest. Since the conservation of energy indicates that there can only be as much kinetic energy as there was potential energy, it was deduced that, if these two values are equal when friction is negligible, energy is conserved. If the two values are not equal, it could indicate energy is not conserved; or more likely that signficant frictional mechanisms need to be accounted for.

II. METHODS AND MATERIALS

A. Popper launches

The popper (Liberty Imports "Jumping Gens"; Allentown, PA) is a yellow, spring-like toy that consists of a ethylene vinyl acetate (EVA) foam head with a conically structured netting attached to it, shown in Fig. 1, with a height of 0.085 m and a mass of 0.0055 kg. The measuring device consisted of two meter sticks that were taped together so that the bottom stick would end at the 0.50 m mark of the top stick. This assembly was propped up by a group member's hands, with the edge

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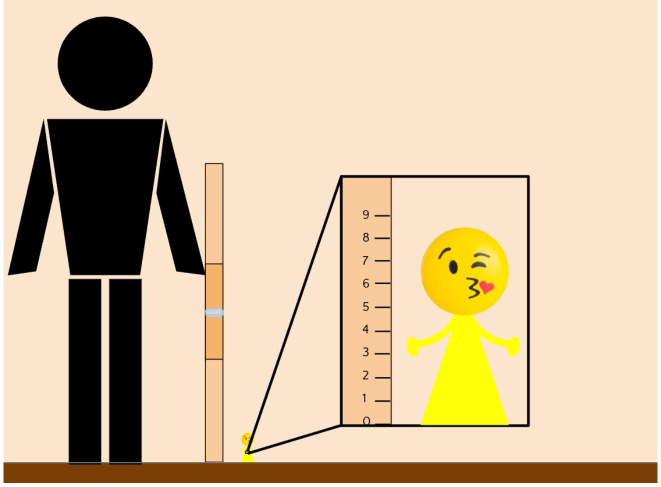

FIG. 1. Setup for the experiment depicting the measuring device and the popper; not to scale.

FIG. 2. Setup for the mechanical work portion of the experiment showing digital scale, popper, and scissor jack. Popper is shown at onset of snap-through instability.

of the ruler staying flat on the ground. Then, a popper was pinched between another group member's thumb and index finger at the side of the foam head to compress it toward $y = 0$, the popper's snap-through point. To release the popper, the thumb and index finger were simultaneously removed from the foam head, allowing the popper to spring upwards and reach its maximum height before moving downwards. For a total of five trials, the same person released each popper with this method for each trial to avoid confounding variables. The popper's maximum height from each trial was documented through visual observation and later, more precisely observed in videos of each trial taken at 60 frame/s with an iPhone 15 (Apple, Inc; Cupertino, CA). These videos were then processed through FizziQ, where each frame was handpicked, and the popper's position was indicated with a point and positioned by a group member [4, 5]. To find the velocity and maximum height with the FizziQ app, each video of each trial was input into the software [5]. After setting the initial position $y = 0\,\mathrm{m}$ and time $t = 0\,\mathrm{s}$, appropriate times during the video were selected that allowed for accurate pinpointing of the position of the popper at that time (see Table I). The experiment was conducted inside a classroom in a secluded area with the windows closed, unaffected by external factors and elements, such as other individuals and wind.

B. Work to compress a popper

To measure the work done in compressing a popper before release, a digital scale (TOP2KG; Smart Weigh; Jiangsu, China) was placed under the popper to measure the mass in grams, and zeroed to avoid counting the popper's deadweight, as shown in Fig. 2. The scissor jack was placed next to the scale so that the platform sat on the popper's foam head. The scissor jack was used to adjust to a specific compression height for each trial, allowing for more exact calculations of force measurements. Additionally, the use of this tool avoided confounding variables like inconsistent human force or human error when handling the popper. With this setup, the scissor jack's platform was lowered, thereby compressing the popper to find more precise measurements of force without human error, shown in Fig. 3. The scale reading was later converted to N using $F = mg$, where $g = 9.8\,\mathrm{m\,s^{-2}}$. The force versus displacement was plotted an a trapezoidal integration method used to determine the work done during launch [6–8].

III. RESULTS

A. Work to compress a popper

Fig. 3, shows the spring force generated by different compression distances. From this, the elastic potential energy stored in the popper before release was calculated as the area under the curve. At the snap-through point, a distance of 0.05 m compressed, the area under the curve was approximately 0.257 J.

B. Popper launches

Table I provides representative kinematics data from FizziQ based on a trial video [5]. Table I shows the maximum height and velocity upon release for each trial. Corresponding values for all trials are compiled in in Table II.

In Table III, the kinetic energy of the system at the moment of release and the potential energy of the system at

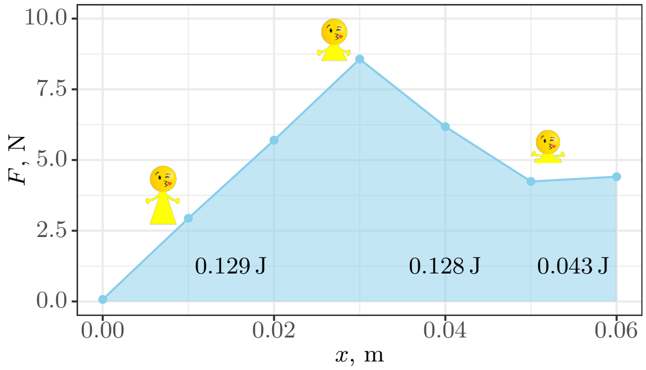

FIG. 3. Graph showing the force in N generated at different compression distances in m. Between 0.03 m and 0.05 m shows the popper's snap-through in which the spring curvature direction reverses. The respective elastic potential energies at 0.03 m, 0.05 m, and 0.06 m are shown as areas under the curve.

TABLE I. One of the tables created by FizziQ, based on a video of the first trial with selected values to be shown, such as the vertical position (height) and the velocity [5]. The maximum height, velocity upon release, and velocity right after hitting the maximum height are marked with a star. The cells without values are intentionally left blank.

t, s	h, m	v, m s^{-1}
0	0.03	
0.03	0.19	* 5.63
0.07	0.39	5.38
0.10	0.57	5.05
0.13	0.71	4.42
0.16	0.85	3.81
0.19	0.96	3.14
0.42	** 1.39	** 0.83
0.68	1.27	

* upon release
** at maximum height

TABLE II. Maximum height, velocity upon release, and velocity at maximum height for each trial

trial	h, m	v_0, m s^{-1}	$v(h)$, m s^{-1}
1	1.39	5.63	−0.83
2	1.41	5.80	−0.38
3	1.54	5.45	−0.22
4	1.42	2.94	−0.10
5	1.63	4.69	−0.13

TABLE III. Kinetic energy upon release, kinetic energy at maximum height, potential energy at maximum height, and the difference between

trial	KE_0, J	$KE(h)$, J	$GPE(h)$, J	$KE_0 - GPE$, J
1	0.086	1.86×10^{-3}	0.074	0.012
2	0.091	3.80×10^{-4}	0.080	0.011
3	0.080	1.31×10^{-4}	0.082	0.002
4	0.028	0.27×10^{-4}	0.074	0.047
5	0.059	4.88×10^{-4}	0.086	0.027

the popper's maximum height were compared. It is important to note that, in Table II, the fourth trial shows a significantly lower velocity than the others, at 2.94 m s^{-1}. This is most likely due to human error, inconsistent release of the popper, or inaccuracy with measurements. This outlier contributed to the overall decrease in kinetic energy and the lower t-statistic.

IV. DISCUSSION

A. Energy is conserved during popper launches

This experiment provides experimental confirmation that energy is conserved when friction is negligible. Although limited by human and experimental error, a general idea for energy conservation was established. As shown in Table III and Fig. 4, the difference between KE and PE was slightly higher than anticipated, with an average difference of about 0.020 J. The data showed a similarity of approximately ±0.1 J between the initial kinetic energy and potential energy at the peak of the launch, averaged across the five trials. This consistency demonstrates that energy was conserved, although any discrepancies may be attributed to limitations of the FizziQ app and human error when releasing the poppers [5]. A significant limitation was that it could not accurately capture the exact moment when the popper began its upward motion, instead registering a few milliseconds later.

A paired t-test was performed to compare the kinetic energy at launch and the potential energy at the popper's maximum height with the values in Table III. As shown, the analysis yielded a t-statistic of $t = -0.89$ and a two-tailed p-value of $p = 0.424$. Since $p = 0.424 > \alpha = 0.05$, there was no statistically significant difference between the kinetic energy at launch and the potential energy at the popper's highest point. This means that energy is conserved within the popper's flight.

Furthermore, the calculated elastic potential energy was 0.257 J, which appears far from the average kinetic energy and potential energy values. A significant amount of energy is lost upon release, especially due to friction between the popper's conical netting. Assuming that

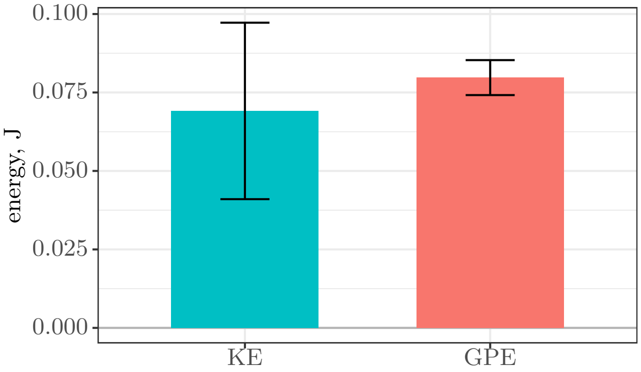

FIG. 4. A bar graph comparing the two primary energy states with standard deviation error bars. Note that KE's error bar length is much larger than GPE's due to Trial 4 (an outlier), which had a much lower velocity of 2.94 m s^{-1}, thus significantly increasing the standard deviation for the KE measurements.

about 73.2 % of the elastic potential energy was lost to friction, heat, and sound, the rest of the elastic potential energy was converted to kinetic energy, which forced the popper upwards and yielded the first two values in Table III. From these we conclude that the major energy loss mechanisms occur during launch and are associated with the popper material or friction during the launch process; not due to drag or other loss during the flight phase. Furthermore, the value of KE_{max} nears 0 in each trial, implying that the popper's kinetic energy at launch was near or completely depleted by the time the popper reached its maximum height. This further supports energy conservation, as the kinetic energy at launch was converted into other energy types, gravitational potential energy being the most prominent, as shown by the close values of KE_r and GPE.

B. Sources of experimental error

Friction was neglected throughout this experiment, but it would still affect the popper as it traveled through the air, contributing to experimental error. In addition to environmental factors, many errors can also be attributed to human error, as visual observation and 60 frame/s videos are not always sufficient in accurately describing exact points, and manual compression and release were likely somewhat biased by the human releaser's reaction time. Future experiments could be improved by performing the experiment in a vacuum, where air resistance is actually negligible, measuring data by more accurate means, such as with high-speed cameras, and using more precise methods of compression and release.

V. ACKNOWLEDGEMENTS

JB assisted with data collection, statistical analysis, creation of visual aids, and documentation and organization of the results and discussion. JK assisted with data collection, statistical analysis, and documentation of the results and discussion. SN assisted with data collection and statistical analysis, and worked on the abstract, results, and discussion. KS assisted with data collection, documentation, and organization of the methods and materials, results, and discussion.

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Journal of Science & Engineering **2**, 94–98 (2026)

Examining energy storage and work done by elastic jumping poppers

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(Received 31 January 2026; accepted 28 March 2026; published 17 May 2026)

This experiment investigated energy storage and work done in elastic jumping poppers as nonlinear elastic systems. The maximum gravitational potential energy during launch was determined from video analysis, while force–displacement measurements obtained during compression were numerically integrated to calculate the work done on each popper. The force–displacement data revealed nonlinear elastic behavior characterized by snap-through instability. The measured launch energies were lower than the work calculated from compression measurements, indicating that although the poppers clearly stored and released elastic energy, the two methods did not produce close quantitative agreement under the conditions of this experiment.

DOI: 10.64808/72j31w22

I. INTRODUCTION

Elastic materials store energy when deformed and release that energy when allowed to return toward an equilibrium configuration [1–5]. While many elastic systems are well approximated by linear force–displacement relationships, real materials and structures often exhibit nonlinear behavior. One important form of nonlinearity is snap-through instability, in which increasing deformation leads to a maximum restoring force followed by a sudden decrease as the system rapidly transitions into a new geometric configuration. This behavior is characteristic of thin shells and domed elastic structures, including the poppers used in this experiment. During snap-through, elastic potential energy is released abruptly, and the structure's internal resistance drops even as displacement increases, producing rapid motion that cannot be accurately described using simple linear elastic models [6, 7].

The concepts of energy conservation and work provide a more general framework for analyzing such systems [1–3]. Mechanical energy exists in multiple forms, including kinetic energy $\mathrm{KE} = \frac{1}{2}mv^2$ and gravitational potential energy, $\mathrm{GPE} = mgh$. In ideal systems, the total mechanical energy remains constant. When an elastic object is compressed, mechanical work is done on the system and stored as elastic potential energy, which may later be converted into kinetic and gravitational energy. For 1D systems with variable force, the work done is given by the integral [1–3]:

$$W = \int F(x)dx \tag{1}$$

According to the work-energy theorem, the net work done on a system is approximately equal to the change in its mechanical energy, allowing independent experimental measurements of work and mechanical energy to be directly compared [1–3, 8].

The purpose of this experiment was to test the general concept of energy conservation, and to analyze rubber jumping poppers as nonlinear elastic systems by (1) measuring maximum gravitational potential energy during launch using video analysis, and (2) determining the work done during compression from force-displacement data. These measurements were used to test whether the energy gained during launch was comparable to the work stored during compression in the presence of snap-through instability.

Based on energy conservation, we hypothesize that the total mechanical work (W) done on the popper during compression should be equal to both the initial kinetic energy (KE_0) on launch and the maximum gravitational potential energy (GPE_f) at the highest point of its flight. Alternatively, if loss mechanisms, such as nonlinear material properties, effects associated with snap-through instability, friction, and air drag, are large, then the kinetic and gravitational potential energies will be less than the mechanical work done:

$$H_0 : W = \mathrm{KE}_0 = \mathrm{GPE}_f \tag{2}$$
$$H_1 : W > \mathrm{KE}_0 > \mathrm{GPE}_f \tag{3}$$

II. METHODS AND MATERIALS

This experiment utilized three toy poppers of different masses ("Jumping Gens"; Liberty Imports; Allentown, PA). These poppers included a heart-eyes emoji popper ($m = 0.0053\,\mathrm{kg}$), a crying emoji popper ($m = 0.0055\,\mathrm{kg}$), and a shocked emoji popper ($m = 0.0057\,\mathrm{kg}$).

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A. Launch kinematics and GPE

Motion during the launches was recorded using an iPhone 16 Pro Max (Apple; Cupertino, CA) positioned perpendicular at a fixed distance of 2.00 m from the launch point, recording at 60 frame/s with a resolution of 1080p. A meterstick was placed in frame for scale.

Each popper was placed on a flat surface (the floor) and launched using a manual downward push, intended to be as consistent as possible across all trials. While the magnitude of the applied force could not be directly controlled or measured, care was taken to apply a similar force during each launch. Three trials were chosen for each popper to balance repeatability with time constraints, and averaging was used to reduce variability from manual launching. A failed launch was defined as any trial in which the popper tipped, slid laterally, failed to fully invert, or did not produce a clear upward trajectory. Repeated trials were conducted to reduce the variability caused primarily by the manual push.

Video data were analyzed using Tracker [9, 10] to determine the maximum height (h) reached in each trial. Digitization proceeded similar to [11–16]. The measured heights were used to calculate the gravitational potential energy reached by each popper at the top of its motion according to:

$$\mathrm{GPE}_f = mgh, \tag{4}$$

where m is mass, and $g = 9.81\,\mathrm{m\,s^{-2}}$.

Variability in launch conditions was reflected in the spread of measured energies and accounted for in our discussion. Subsequent graphs and statistical analyses were performed in Python using the `numpy` and `matplotlib` libraries [17–19].

B. Mechanical work during compression of poppers

To determine the work done in compressing each popper, force-displacement measurements were obtained using a standard laboratory scissor jack and a digital scale (TOP2KG; Smart Weigh; Jiangsu, China). Each popper was placed between the scissor jack and the scale and compressed in increments of 0.005 m. The force exerted by the popper (as read on the digital scale, converted according to $F = mg$) was recorded at each displacement. Compression continued up until and slightly beyond snap-through instability occurred, indicated by a sudden decrease in measured force as the popper physically inverted.

Force-displacement data were collected for the three respective poppers to provide reasonable average data. Work was calculated by numerically integrating the force-displacement data using the trapezoidal rule [17, 18, 20], which estimates the area under the force-displacement curve without assuming linear elasticity.

Data and analyses are available at `https://github.com/devangel77b/427bdemairo-lab3`.

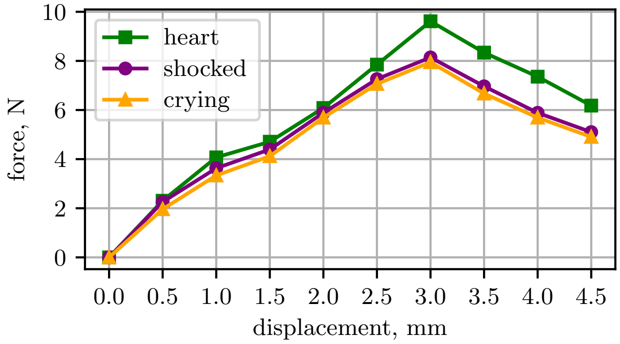

FIG. 1. Compressional displacement vs. elastic force for all three poppers.

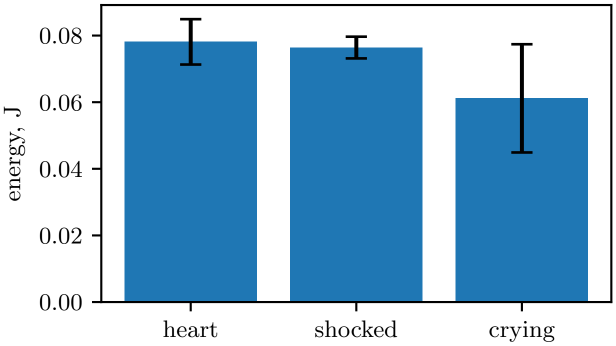

FIG. 2. Average maximum gravitational potential energy for all three poppers (J).

III. RESULTS

The graph shown in Fig. 1 shows a roughly linear relationship between the elastic force of all of the poppers and the compressional displacement up until it reaches the snap-through instability point, which can be seen at the peak of the graph, after which the relationship trends downwards due to the conical nature of the popper's spring. From the experimental results, we can see that the force of the heart-face popper remains consistently higher than the shocked-face popper, indicating that the heart-face popper exhibited greater effective stiffness over the initial compression range. The same trend applies to the shocked-face popper compared to the crying-face popper. From this, we can conclude that the heart-face popper has the highest elastic stiffness of all three poppers. Furthermore, we can conclude that the snap-through instability point occurs at a compression of approximately 0.03 m, as indicated in Fig. 1.

Video analysis was used to determine the maximum height reached by each popper in each trial. Using these measured heights, the poppers' maximum gravitational

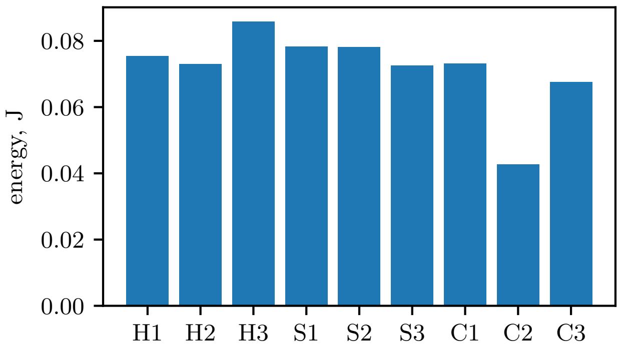

FIG. 3. Per-trial maximum gravitational potential energy for all three poppers (J).

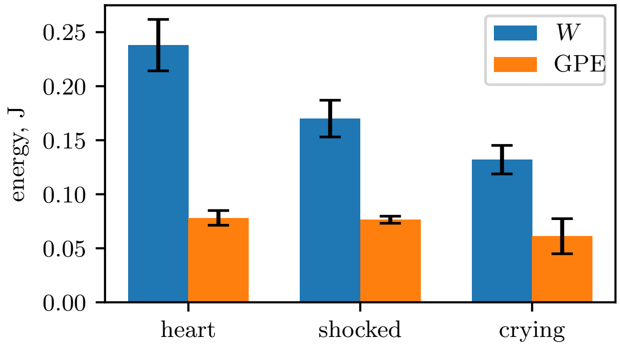

FIG. 4. Comparison of work done during compression and maximum gravitational potential energy gained during launch.

potential energy was calculated, resulting in average values of 0.0781 J for the heart-eyes popper, 0.0764 J for the shocked popper, and 0.0611 J for the crying popper, as shown in Figs. 2 and 3. Individual trials showed variation due primarily to differences in manual launch force. The heart-eyes popper achieved a mean peak GPE of 0.0781 ± 0.0068 J, the shocked popper 0.0764 ± 0.0033 J, and the crying popper 0.0611 ± 0.0162 J. A one-way ANOVA revealed no statistically significant difference in launch GPE across the three popper designs ($F(2,6) = 2.45$, $p = 0.167$). The observed ranking (heart-eyes > shocked > crying) is therefore descriptive rather than statistically confirmed, a limitation attributable primarily to the small sample size of three trials per popper.

Work calculated from force-displacement integration was greater than the maximum gravitational potential energy measured from video analysis for all three poppers, as shown in Fig. 4. This indicates that the two methods did not produce close quantitative agreement under the conditions of this experiment.

IV. DISCUSSION

A. Energy is conserved

The results of this experiment demonstrate that elastic jumping poppers store mechanical energy during compression and release this energy through snap-through instability during launch. Video analysis showed that each popper gained measurable gravitational potential energy during flight, while force–displacement measurements revealed nonlinear elastic behavior that cannot be accurately modeled using Hooke's Law ($F = kx$, where force is proportional to displacement in linear elastic systems) alone. Although variability was introduced by manually applied launch forces and measurement uncertainty, repeated trials and averaging produced consistent trends across all poppers.

However, the work values obtained from force–displacement integration were significantly larger than the maximum gravitational potential energy values measured from launch height (Fig. 4). This lack of close agreement suggests either substantial energy losses, overestimation of compression work from friction between the popper and scissor-jack platform, or additional uncertainty in the experimental methods. Therefore, while the experiment clearly demonstrated elastic energy storage and release, it did not support the null hypothesis that work done during compression is approximately equal to the mechanical energy gained during launch. The paired t-test ($t(2) = 4.05$, $p = 0.056$) approached but did not reach conventional significance, given the small sample; however, the mean recovery of only 41.3% of compression work as launch GPE represents a practically large discrepancy unlikely to result from measurement uncertainty alone. The ANOVA across poppers ($F(2,6) = 2.45$, $p = 0.167$) confirmed that differences in launch GPE among the three designs were not statistically distinguishable at this sample size, so the ranking of heart-eyes > shocked > crying should be treated as descriptive.

Variability in measured energy values is primarily due to the use of a manual launch force, which could not be directly controlled or measured in a consistent manner. However, repeated trials and averaging helped reduce this variability and revealed consistent overall trends. The experiment successfully demonstrated that poppers can be analyzed as elastic systems using energy methods, while also highlighting the limitations of assuming close quantitative agreement between compression work and measured launch energy in a real nonlinear system. These results indicate that poppers can be effectively modeled using energy concepts, while also emphasizing the effects of experimental uncertainty and non-ideal energy transfer.

B. Energy loss during launch process is significant

If the system were ideal, max GPE should equal compression work. The observed mean loss of 58.6% can be partially attributed to known physical mechanisms. The coefficient of restitution for natural and silicone rubber falls in the range 0.70–0.85 [4, 5, 21]; using a midpoint value of 0.78, viscoelastic hysteresis alone accounts for approximately 39% energy loss ($1 - e^2 = 1 - 0.61$). Snap-through instability dissipates additional energy as acoustic emission and structural vibration during inversion, estimated at approximately 7% [6, 7, 22–24]. Air drag on a low-mass (≈ 5 g), low-velocity (≈ 9 m/s) object contributes an estimated 3%, computed from $F_d = \frac{1}{2}\rho C_d A v^2$ with $C_d \approx 0.47$ for a hemisphere and $A \approx 5 \times 10^{-4}$ m^2 [1, 3]. Together, these mechanisms account for approximately 49% of the energy input, leaving a residual unexplained loss of roughly 9.5% that likely reflects friction between the popper and scissor-jack platform during compression, which would systematically inflate the calculated work integral.

The three poppers also showed a consistent ranking in both stiffness and launch energy: the heart-eyes popper exhibited the steepest force–displacement slope and achieved the highest mean launch GPE (0.0781 J), while the crying popper, despite being intermediate in mass at 0.0055 kg, achieved the lowest GPE (0.0611 J), with the shocked popper intermediate in both. This suggests that small variations in dome geometry and rubber composition have a larger influence on energy storage [6, 7, 22, 23] than the modest mass differences among the three designs. However, as noted above, the ANOVA ($p = 0.167$) did not confirm these differences as statistically significant; a larger number of trials per popper would be required to determine whether the ranking reflects genuine design differences or sampling variability from the manual launch procedure.

V. ACKNOWLEDGEMENTS

BD was responsible for experimental setup, data collection, data organization, and the verification of graphs and calculations. AL was responsible for verifying results, drafting results and conclusions, and incorporating necessary revisions. IS was the primary author of the abstract, introduction, and discussion sections, and was responsible for conceptual framing, verification of data and measurements, and the generation and validation of major graphs and calculations. AD assisted in data collection from video analyses. We thank several anonymous peer reviewers and we thank our classmates for their collaboration in collecting and verifying measurements, assembling the necessary materials, and contributing to the accuracy and reliability of the results.

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Journal of Science & Engineering **2**, 99–101 (2026)

Analysis of energy transformation in a non-ideal spring popper

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(Received 30 January 2026; accepted 31 March 2026; published 17 May 2026)

This experiment looks at how energy is transformed in a spring-loaded toy popper by comparing the work done to compress it with the gravitational potential energy it has at its highest point. Using a scissor jack and a high-precision scale, the work input (W) was calculated using the trapezoidal Riemann sum of the force-displacement curve, totaling 0.255 J. Following ten launch trials of the popper, we observed maximum height $h = 1.12 \pm 0.11\,\mathrm{m}$, corresponding to gravitational potential energy (GPE) of $0.062 \pm 0.006\,\mathrm{J}$. The results indicate a large mechanical energy loss of $76 \pm 2\,\%$. This discrepancy is likely due to non-conservative forces, such as friction or aerodynamic drag during flight. This system illustrates the substantial role of energy dissipation in non-ideal mechanical systems such as this one.

DOI: 10.64808/8gevmp74

I. INTRODUCTION

The law of conservation of energy states that energy is neither created nor destroyed, only transformed [1–3]. However, in most real-life situations, some energy is transferred into forms that are not part of the mechanical energy being measured.

In our present experiments, we examine energy conservation in small jumping popper toys. Work is performed to compress the popper, storing elastic potential energy. Upon release, this energy converts to kinetic energy and then gravitational potential energy (GPE). This study treats the work input and the potential energy output as independent datasets. We hypothesize that if the popper were a perfectly conservative mechanical system, then the work input (W) would equal the gravitational potential energy at peak height, because the total mechanical energy would be conserved with no losses.

However, in this system, non-conservative processes are expected to reduce the fraction of mechanical energy that is converted into gravitational potential energy. For example, the elastomer material of the popper may lose energy to heat when strained, since such deformation is a highly dissipative process [4]. Therefore, we consider as an alternative hypothesis that the measured GPE could be lower than the work input, since not all stored elastic energy is transferred into kinetic energy or gravitational potential energy during release.

II. METHODS AND MATERIALS

The experiment was conducted using a toy popper (“Jumping Gens”; Liberty Imports; Allentown, PA) consisting of a ethylene vinyl acetate (EVA) foam head and body, where the spring is located, a scissor jack, a smartphone for video recording, a meter stick, and a digital scale (TOP2KG; Smart Weigh; Jiangsu, China). The mass of the popper was 0.0056 kg.

A. Initial elastic potential energy

To determine the work performed while the popper was compressed, the scale was placed on the lower surface between the two surfaces of the scissor jack, with the popper on top of the scale. Then, in 0.005 m increments, the top surface of the scissor jack was lowered by turning the knob slowly, which compressed the popper. The mass displayed on the scale was recorded for each increment until the popper was fully compressed and the scissor jack could not be lowered any further. This occurred after a displacement of 0.060 m. At each interval, the mass from the scale was recorded and converted to force ($F = mg$) using $g = 9.8\,\mathrm{m\,s^{-2}}$ [1–3]. Work (W) is given by [1–3]

$$W = \int F dx, \tag{1}$$

which we approximated by numerically integrating the area under the force-displacement curve using the trapezoidal Riemann sum [5–8]:

$$W \approx \frac{\Delta x}{2}\left[f(x_0) + 2f(x_1) + 2f(x_2) + \cdots + 2f(x_{n-1}) + f(x_n)\right]. \tag{2}$$

B. Final gravitational potential energy

Once the procedure and calculations to find the work input were completed, another procedure was followed

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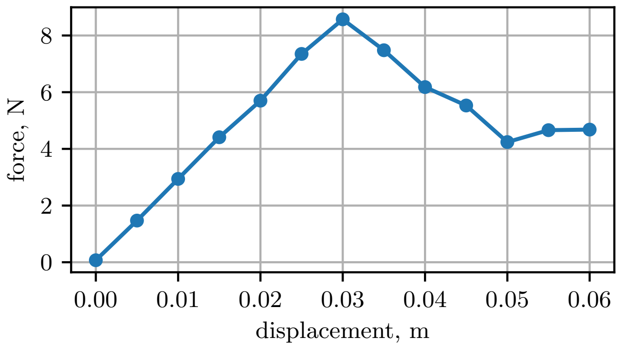

FIG. 1. Force versus displacement of the popper as it is being compressed.

to find the gravitational potential energy (GPE) of the popper at its maximum height. Two fingers were placed on each side of the popper's foam head to compress it, and then released quickly to trigger launch. At the same time, a meter stick was held in place and a video recording was used to capture the height of the popper. The maximum height (h) for each trial was recorded for ten trials. The average height and other summary statistics were then used to determine the final GPE of the system, where GPE is given by [1–3, 9]:

$$\mathrm{GPE} = mgh, \tag{3}$$

where $g = 9.8\,\mathrm{m\,s^{-2}}$.

Once the work and gravitational potential energy were calculated, the percentage of energy lost was found to show how much of the input energy was not converted into gravitational potential energy. Raw data and analysis code are available at `https://github.com/devangel77b/427safzal-lab3`.

III. RESULTS

The force-displacement behavior of the popper during compression is shown in Fig. 1. The maximum height measurements from the ten launch trials are shown in Table I. A statistical summary of those measurements is shown in Table II.

The total work calculated from the force-displacement data shown in Fig. 1 using the trapezoidal Riemann sum formula was 0.255 J. As shown in Table II, the maximum height over $n = 10$ trials was 1.12 ± 0.11 m (mean ± 1 sd). Using (3) gives an estimate of the gravitational potential energy of 0.062 ± 0.006 J.

TABLE I. Maximum height reached by the popper across ten trials.

trial	height, m
1	1.14
2	1.15
3	1.05
4	1.09
5	1.11
6	1.41
7	1.02
8	1.06
9	1.12
10	1.08

TABLE II. Statistical summary of maximum height measurements from popper trials.

quantity	value, m
mean	1.123
median	1.100
standard deviation	0.106
SEM	0.033
quartile 1	1.060
quartile 3	1.140
interquartile range	0.080

IV. DISCUSSION

A. Large fraction of the initial elastic stored energy is lost during the launch process

Comparing the input and output energy shows a large difference:

$$\begin{aligned} E_{lost} &= E_{in} - E_{out} \\ E_{lost} &= 0.255\,\mathrm{J} - 0.062 \pm 0.006\,\mathrm{J} = 0.193 \pm 0.006\,\mathrm{J} \end{aligned} \tag{4}$$

This corresponds to $76 \pm 2\,\%$ of the initial elastic potential energy, stored when the popper is compressed, is unaccounted for.

Some amount of energy loss is expected for a real, non-ideal system and can be explained by several factors. During the compression process, the plastic experiences internal friction as it deforms, which converts some energy into heat. Second, not all motion is perfectly vertical. Most trials resulted in the popper being launched at some angle rather than perfectly straight upward. If the popper tilts or spins, some energy goes into horizontal or rotational motion, neither of which was measured in this experiment. Air resistance also does negative work on the popper as it moves upward.

The force-displacement relationship of the popper does not follow Hooke's law. Instead, the data show a nonlinear relationship, indicating that the popper does not behave as an ideal linear spring [1–3, 10], especially as the spring experiences a snap-through instability. The arrangement of the popper spring as a series of filaments that are free to rub on one another suggests a mechanism of loss due to friction as this nonlinear spring uncompresses.

B. Effect of outlier

In addition, it is possible that the percentage of energy lost may be slightly overestimated because of a potential high outlier in the dataset. According to Table I, the sixth trial resulted in a height of 1.410 m. Using the quartile data represented in Table II, the formula for high outliers gives [11]:

$$\text{high outlier} > Q_3 + (1.5 \times \text{IQR}) \tag{5}$$

$$1.410 > 1.260 \tag{6}$$

Taking this high outlier into account, along with the fact that the mean of 1.123 m is greater than the median of 1.100 m, the data are moderately skewed to the right. However, this does not necessarily mean the value from trial 6 is invalid, only that it is unusually large compared to the rest of the dataset. To determine whether this outlier is statistically significant relative to overall variation, the standard deviation (0.106 m) was used to calculate the z-score, assuming normality [11]:

$$z = \frac{x - \mu}{\sigma} \tag{7}$$

$$z \approx 2.71 \tag{8}$$

The z-score represents how many standard deviations the maximum height from trial 6 is above the mean. Since values above about two standard deviations are generally considered unusually far from the mean, the 1.410 m trial is a statistically significant high deviation. Despite this, the rest of the dataset remains relatively consistent, since the standard deviation (0.11 m) is small compared to the mean height (1.12 m), indicating a moderate spread rather than extreme variability.

Overall, the results support the hypothesis that gravitational potential energy is lower than the work input, as a substantial discrepancy of $76 \pm 2\,\%$ was observed between the calculated work and the measured GPE. This difference indicates that the system is non-conservative, with mechanical energy not fully transferring into gravitational potential energy. This is likely due to multiple non-conservative processes, including friction, internal energy dissipation during deformation of the popper, and aerodynamic drag. While the exact contribution of each mechanism was not directly measured, the magnitude of the difference suggests significant energy transformation into forms that are not mechanical.

V. ACKNOWLEDGEMENTS

SA developed the hypothesis, calculated data, and created graphs for evaluation of that hypothesis. AM performed much of the experiment by operating the scissor jack, and SD helped capture measurements such as the mass and displacement.

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Journal of Science & Engineering **2**, 102–105 (2026)

Investigation of energy conservation using poppers

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(Received 30 January 2026; accepted 11 April 2026; published 17 May 2026)

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.

DOI: 10.64808/mjhvfp73

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:

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

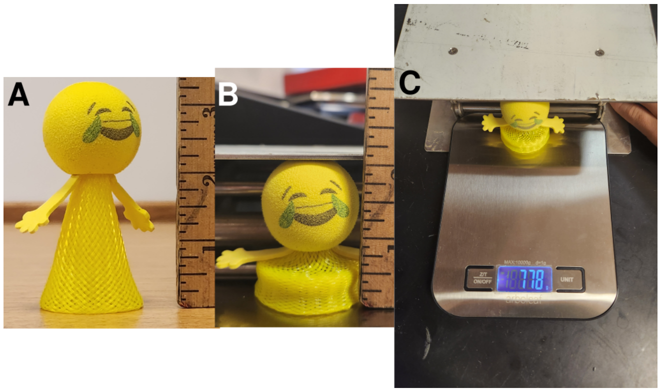

FIG. 1. (A) Uncompressed popper. (B) Compressed popper. (C) Setup for measuring mechanical work using digital scale and scissor jack.

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-

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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

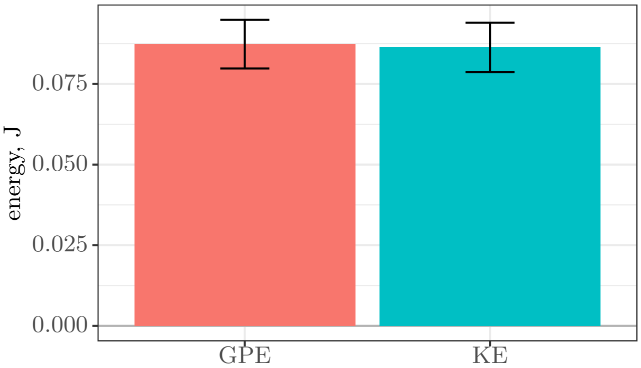

FIG. 2. Bar graph of kinetic and potential energies; data from Table I. KE and PE are not significantly different (ANOVA; $p = 0.836$).

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

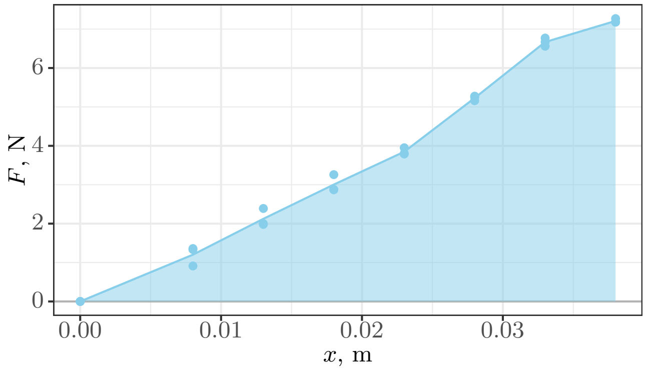

FIG. 3. Force (N) versus compression (m); data from Table II. The work done to compress the popper (shaded area) is $W = 0.130 \pm 0.001$ J.

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

We thank the Science & Engineering Program at Manalapan High School for support. NB helped with methods and materials and results. KK completed the abstract, carried out the t-test, and wrote about its results. EP helped with the launch procedure, did the video motion analysis, worked on introduction, methods and materials, and discussion, and handled initial and final revisions.

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Journal of Science & Engineering **2**, 106–109 (2026)

Testing energy conservation through popper launch and compression experiments

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(Received 30 January 2026; accepted 31 March 2026; published 17 May 2026)

The principle of energy conservation predicts that energy is never lost; it only changes forms. To test this principle experimentally, we launched popper toys that, when compressed, store elastic potential energy, which is converted into kinetic energy and gravitational potential energy as the popper launches. We also compressed the popper to determine the total elastic potential energy stored in it before launch. Ultimately, by comparing the kinetic and potential energies at different stages of the launch and assuming negligible air resistance, we found convincing evidence that mechanical energy is not constant; however, this does not imply that energy is not conserved, considering we failed to account for air resistance.

DOI: 10.64808/q69tgd65

I. INTRODUCTION

Kinetic energy is the energy associated with the motion of an object and represents the work done to speed up an object to a certain velocity. It is a scalar quantity that increases with both mass and velocity and is given by [1–3]:

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

Potential energy is the energy associated with the position of an object. Each conservative(i.e. path-independent) force gives rise to a different form of potential energy, but in general, the change in potential energy of conservative forces is given by the following integral [1–3]:

$$\Delta\mathrm{PE} = -\int \vec{F} \cdot d\vec{x}. \tag{2}$$

Note that this implies that we can find the area under the curve of the graph of F vs x and use this to find total potential energy. Considering (2) with F being given by the force of gravity, which is mg in the negative direction, with $g = 9.8\,\mathrm{m\,s^{-2}}$, we find gravitational potential energy at h to be given by [1–3]:

$$\mathrm{PE} - 0 = -\int_0^h -mg dy. \tag{3}$$

Using the reverse power rule, we find the indefinite integral and find the difference of it evaluated at the upper and lower bounds as follows [1–3]:

$$\mathrm{PE} = mgy\Big|_0^h = mgh. \tag{4}$$

The sum of the total kinetic and potential energies of a system is known as mechanical energy. According to the principle of energy conservation, in the absence of nonconservative forces such as drag and friction, mechanical energy within a system remains constant.

In an effort to test the accuracy of this principle, we launched poppers and observed whether energy was conserved as elastic potential energy is converted into kinetic energy, which becomes gravitational potential energy. That is, we tested to see if the kinetic energy of the poppers right after launch (KE_0) was equal to the gravitational potential energy when the poppers reached their maximum height (GPE_f). Our null hypothesis and alternative hypothesis were:

$$H_0 : \mathrm{KE}_0 = \mathrm{GPE}_f, \tag{5}$$
$$H_a : \mathrm{KE}_0 \neq \mathrm{GPE}_f. \tag{6}$$

We also analyzed the mechanical work done in compressing the poppers, in order to determine the total energy stored in the form of elastic potential energy prior to launch:

$$W = \int \vec{F} \cdot d\vec{x}. \tag{7}$$

The work done, and the elastic potential energy prior to launch, should also be equal in magnitude to the kinetic energy at launch in an ideal system. In a real system, however, friction and other nonconservative forces are expected to dissipate some portion of the energy, resulting in $\mathrm{KE}_0 < W$. Computing W allows us to examine if energy loss is occurring primarily during the launch process, i.e. $W > \mathrm{KE}_0$, or if energy loss is dominated by in-flight mechanisms like friction, i.e. $\mathrm{KE}_0 > \mathrm{GPE}_f$.

II. METHODS AND MATERIALS

In our experiment, we utilized a 5.7 g crying emoji popper toy (“Jumping Gens”; Liberty Imports; Allentown, PA) made of a ethylene vinyl acetate (EVA) foam head and body (i.e. coefficient of restitution $COR = 0.7$ to 0.95)[4].

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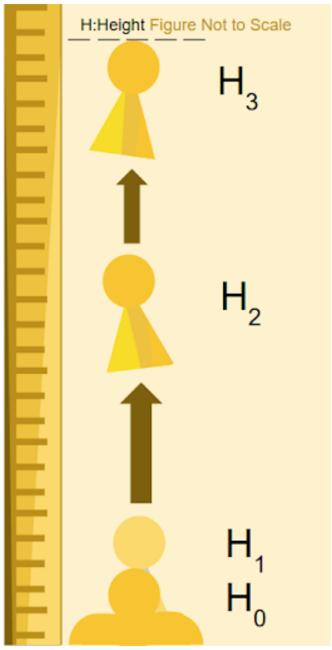

FIG. 1. Popper launch mechanism.

A. KE_0 and GPE_f measurements

Popper launch kinematics were recorded using a Smartphone (S25; Samsung; Suwon, South Korea) operated at 120 frame/s. To provide scale calibration, we placed two metersticks in the frame and used a bubble level to ensure the metersticks were aligned vertically.

To measure the velocity of the popper at launch, we recorded the launch frame by frame and calculated the velocity of the popper by multiplying the frame rate by the distance traveled between a single frame. Note that we measure the velocity over as short a time period as possible to reduce error due to gravitational acceleration. We then used (1) to calculate the kinetic energy of the popper based on its initial velocity (KE_0). We also measured the maximum height reached by the poppers using the video recordings. We then used (4) to calculate the gravitational potential energy at the maximum height (GPE_f). The various stages of the launch of the popper as well as our experimental setup is show in Fig. 1 and the data collected from our launches is shown in Table I. We then applied a *t*-test to see if the difference $KE_0 - GPE_f$ was significantly different from zero [5–8].

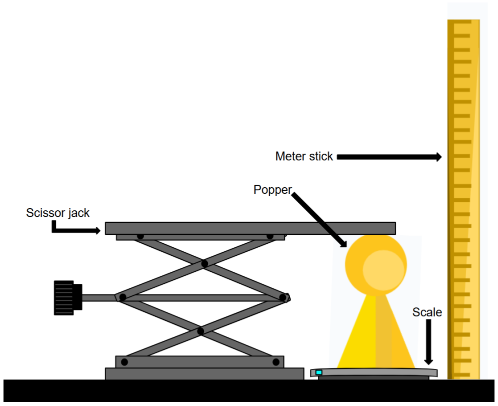

FIG. 2. Scissor jack setup

TABLE I. Observed kinetic and potential energy

trial	KE_0, J	GPE_f, J	$KE_0 - GPE_f$, J
1	0.103	0.076	0.027
2	0.080	0.075	0.005
3	0.120	0.081	0.039
4	0.113	0.078	0.035
5	0.138	0.083	0.055
6	0.113	0.084	0.030
7	0.136	0.076	0.060
8	0.138	0.081	0.057
9	0.158	0.083	0.075
10	0.120	0.077	0.043
11	0.174	0.092	0.082
12	0.148	0.078	0.070

B. W measurement

To measure the mechanical work done in compressing the popper, we placed the popper on top of a digital scale (Arboleaf CK10I; Plano, TX) to measure force, as seen in Fig. 2. We used a scissor jack (8 inch × 8 inch area, min height 3 inch) with ruler clamped to a ringstand for distance measurements. We zeroed the scale and the ruler at the point where the scissor jack was just touching the head of the popper. We then lowered the scissor jack in increments of 0.005 m. Scale readings were converted to N using $F = mg$. We conducted two replicates from unloaded to fully compressed. (7) was used to find the mechanical work done in compressing the popper. The area under the resulting curve was numerically integrated using the trapezoid method [6, 9].

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

III. RESULTS

From this data set, we find the sample mean and sample standard deviation of the difference in kinetic and potential energy to be 0.048 J and 0.022 J, respectively. This gives a test statistic of 7.44, which gives a two-sided p-value of 1.29×10^{-5}.

TABLE II. Elastic force versus displacement for poppers

displacement x, m	force F, N
0.005	1.49
0.005	1.47
0.010	2.74
0.010	2.88
0.015	4.30
0.015	4.31
0.020	5.91
0.020	5.49
0.025	7.92
0.025	7.42
0.030	6.49
0.030	7.01
0.035	5.49
0.035	5.85

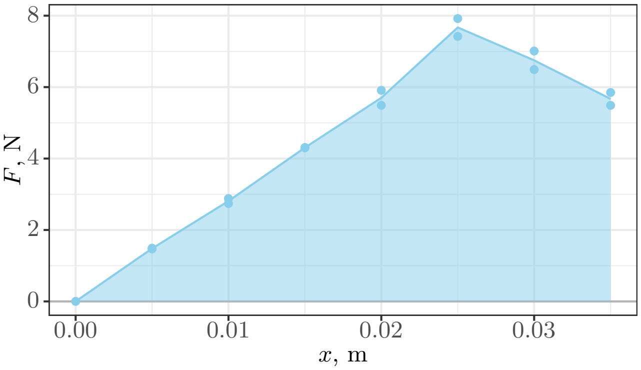

FIG. 3. Spring force (N) vs. displacement (m). The work done in compressing the popper is 0.1573 J.

Using the trapezoidal rule and averaging over points, we can calculate the work to compress the popper, and the energy stored within the spring to be 0.1573 J.

IV. DISCUSSION

A. Energy loss mechanisms unaccounted for

Our p-value of 1.29×10^{-5}, which is far less than any reasonable significance level, leads us to reject our null hypothesis, suggesting that we have found convincing evidence that energy is not conserved when launching poppers. However, considering we did not account for the force of air resistance, this conclusion does not conclusively support that energy is not conserved. In fact, analyzing the data, it is clear that the potential energy was always less than the kinetic energy, which makes sense because energy was dissipated over time due to friction with air molecules.

Our value for the elastic potential energy stored within the spring was greater than the initial kinetic energy with which the popper was launched for all the trials except for one, contradicting energy conservation, which would suggest the two forms of energy to be equal. This can be attributed to our use of an inconsistent human hand-based popper launch that does not fully compress the poppers. Moreover, if launches are not perfectly vertical, some of the popper's kinetic energy can go to the horizontal direction which we have no way of accounting for with our setup. In future experiments, a consistent and standardized way to compress the popper before launching is needed to address these issues.

B. Inelastic energy loss

Another source of error would be poppers holding less elastic energy over time due to repeated stretching and the gradual breakdown of their elastic material. When analyzing the spring force at different displacement values, we observed that the spring followed the linear nature of Hooke's law [1] with $r^2 = 0.99$,

$$F = kx \tag{8}$$

However, at a displacement of approximately 0.025 m, the graph deviated from Hooke's law, with successive measured force values decreasing rather than increasing. We hypothesize that this occurred because the spring buckled at this displacement, causing it to no longer deform elastically and resulting in a significantly reduced measured force. This loss of elastic behavior can be interpreted in terms of the coefficient of restitution, a measure of how well a system returns energy when deformed. As the spring buckled, energy was dissipated through internal friction rather than stored elastically.

C. Air resistance

To test if the magnitude of mechanical energy loss can be reasonably accounted for by air resistance, we performed a scaling calculation by calculating the work due to air resistance. To do this, we integrated the drag force

$$F = \frac{1}{2}\rho C_d A v^2 \tag{9}$$

with respect to x, applying the chain rule and reverse power rule, to find that

$$W_d = \frac{1}{2}\rho C_d A \int v^2 dx, \tag{10}$$

$$= \frac{1}{2}\rho C_d A \int_0^{\frac{v_0}{g}} v^2 \frac{dx}{dt} dt, \tag{11}$$

$$\approx \frac{1}{2}\rho C_d A \int_0^{\frac{v_0}{g}} (v_0 - gt)^3 dt, \tag{12}$$

$$\approx \frac{\rho C_D A v_0^4}{8g}. \tag{13}$$

Note that we did not account for the air resistance's effect on the velocity in the integral, but this will not have a large affect on our results and is valid for or scaling/estimating purposes. Setting drag coefficient $C_d = 1.0$, $\rho = 1.225\,\mathrm{kg\,m^{-3}}$ for the density of air [1], $A = 1{\times}10^{-3}\,\mathrm{m^2}$ for the cross sectional area of the popper, and $v_0 = 5.1\,\mathrm{m\,s^{-1}}$ (i.e. the minimum launch velocity we observed) as the initial velocity, we find that

$$W_d = 0.011\,\mathrm{J} \tag{14}$$

If we instead use the maximum launch velocity we observed ($7.6\,\mathrm{m\,s^{-1}}$), we find

$$W_d = 0.052\,\mathrm{J} \tag{15}$$

These two estimates bracket the energy differences in Table I, supporting the idea that the observed energy losses between $\mathrm{KE}_0 - \mathrm{GPE}_f$ may be due to air resistance.

V. ACKNOWLEDGEMENTS

JCC, JJC, JC, BK, AS, and DP collected the data. DP wrote the abstract, introduction, results, and part of the discussion. BK and AS wrote the Methods and Materials and created the figures. JCC wrote part of the discussion and labelled all figures.

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Journal of Science & Engineering **2**, 110–113 (2026)

Work input and launch height of an elastomeric popper: a quantitative study

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(Received 29 January 2026; accepted 11 April 2026; published 17 May 2026)

This study quantifies the relationship between mechanical work applied during compression of an elastomeric popper and the maximum height achieved at launch. Five compression depths (1.0 cm to 4.5 cm) were each replicated three times, yielding 15 trials total. Work input was determined via trapezoidal Riemann sums of force-displacement data collected with a calibrated scissor jack and digital force gauge. Initial launch velocity was extracted frame-by-frame using Tracker video analysis software (60 frame/s), and maximum height was measured optically against a calibrated scale. Results show strong positive linear correlations between work input and both launch kinetic energy ($R^2 = 0.998$) and peak gravitational potential energy ($R^2 = 0.997$). Across all compression levels, an average of 54 ± 1 % of the compression work was lost prior to launch, consistent with published hysteresis losses for natural rubber under rapid inversion. The remaining 1 % conversion loss from kinetic to gravitational potential energy is attributed to aerodynamic drag and is consistent with a simple drag estimate. These results confirm the hypothesized positive correlation between work input and launch height and are quantitatively consistent with conservation of energy when dissipative mechanisms are properly accounted for.

DOI: 10.64808/9p4r7z72

I. INTRODUCTION

Elastomeric hemispherical shells, commonly marketed as toys called “poppers,” serve as accessible laboratory models for studying energy storage and conversion. When mechanically inverted and compressed below their snap-through threshold, these devices store elastic strain energy [1, 2]. Right after the release, a rapid change in shape converts stored elastic potential energy into kinetic energy, pushing the shell vertically. The work-energy theorem says that the net work done on a system should equal the change in kinetic energy [3–5]. This implies that increasing the mechanical work input while we compress the popper should produce a relatively proportional increase kinetic energy at launch and, therefore, in maximum height attained by the popper.

A critical thing we need to consider is energy dissipation. Elastomeric materials exhibit hysteresis, so energy stored during deformation is not able to be completely recovered upon release, with a fraction of the energy being converted to thermal energy via friction [6, 7]. A secondary source of loss is acoustic emission during the snap event. During flight, aerodynamic drag removes a small additional fraction of kinetic energy. The goal of this study is to (1) confirm a positive correlation between work input and launch height across multiple independently varied compression levels, (2) measure the overall energy budget quantitatively, and (3) compare observed losses to published bounds.

FIG. 1. Scissor jack and scale

We hypothesized that maximum launch height would increase monotonically with work input, and that energy losses between compression work and launch kinetic energy would fall within the 70 % to 90 % range reported in the literature for rapid rubber inversion [7].

II. METHODS AND MATERIALS

A. Apparatus

An elastomeric popper (Liberty Imports; Allentown, PA; mass $m = 5.70 \pm 0.05$ g), measured on a digital balance) was used for all trials. Compression was applied using a scissor jack fitted with a flat aluminum plate to ensure uniform loading across the rim. The force of compression was measured with a digital scale (SmartWeigh; Jiangsu, China) mounted between the scissor jack and

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the popper. Displacement was measured with a ruler. Two vertical meter sticks were placed to a wall and aligned in the camera's field of view to provide a height reference. Launches were recorded at 60 frame/s with a fixed iPhone camera (Apple; Cupertino, CA) placed 1.5 m from the apparatus at a horizontal distance sufficient to keep the entire trajectory in frame.

B. Compression work measurement

To quantify work input, a scissor jack compressed the popper against a digital scale (TOP2KG; Smart Weigh; Jiangsu, China). For all of the five compression depths (1.0 cm, 2.0 cm, 3.0 cm, 4.0 cm and 4.5 cm), the scissor jack was advanced in 1 cm then 0.5 cm increments and we measured the force. Each full force-displacement curve was replicated three times on separate times to see if we could reproduce the measurements. The total mechanical work W for each compression depth was calculated using a trapezoidal Riemann sum [8]:

$$W = \sum \frac{1}{2}(F_i + F_{i+1})(\Delta x) \tag{1}$$

where F_i is the force at displacement step i and $\Delta x = 0.005\,\mathrm{m}$. All force values were recorded directly in N from the gauge display; no unit conversions were required.

C. Launch velocity and height analysis

Video files were imported into Tracker (Open Source Physics, v6.1.5) and calibrated using the known meter-stick spacing [9, 10]. Methods for obtaining launch kinematics were similar to [11–16]. Initial launch velocity v_0 was determined by tracking the centroid of the popper across three consecutive frames immediately after liftoff (frames 1–3 post-release), yielding two independent velocity estimates that were averaged. Peak height was seen as the frame in which the popper's top reached its maximum vertical level before it started to fall down. This was seen against the meter-stick background in the same frame. All distances are reported in m.

D. Energy calculations

Initial kinetic energy (KE) and peak gravitational potential energy (GPE) were calculated independently using [3–5]:

$$KE = \frac{1}{2}mv_0^2, \tag{2}$$

$$GPE = mgh, \tag{3}$$

TABLE I. Force-displacement data, $n = 3$ replicates

x, m	F, N		
0.000	0.0	0.1	0.0
0.005	1.2	1.5	1.4
0.010	2.7	3.1	2.9
0.015	4.4	4.0	4.2
0.020	5.3	5.9	5.8
0.025	7.5	7.0	7.1
0.030	6.5	7.1	6.8
0.035	5.3	6.0	5.7

where $m = 0.0057\,\mathrm{kg}$ and $g = 9.81\,\mathrm{m\,s^{-2}}$. KE and GPE were calculated independently from v_0 and h respectively; neither was derived from the other. The energy retained from compression to launch was computed as

$$\eta = \frac{\mathrm{KE}_0}{W} \times 100\,\%. \tag{4}$$

A paired t-test ($\alpha = 0.05$ significance level) was used to compare work input to GPE at peak height across the 15 individual trials [17–20].

E. Drag estimation

Work done by drag during flight was estimated using the following relationships [3, 5]:

$$F_{drag} \approx 0.5 \rho C_D A v_{avg}^2, \tag{5}$$

$$W_{drag} \approx F_{drag} h, \tag{6}$$

where $\rho = 1.20\,\mathrm{kg\,m^{-3}}$, $C_D = 0.47$, $A = 7.1 \times 10^{-4}\,\mathrm{m^2}$, and $v_{avg} \approx \frac{v_0}{2}$. A typical 3 cm trial ($v_0 = 7\,\mathrm{m\,s^{-1}}$, $h = 0.8\,\mathrm{m}$) yielded $W_{drag} \approx 0.004\,\mathrm{J}$. This calculated 1 % loss closely matches the observed 1 % mean loss, confirming aerodynamic drag as the primary dissipative mechanism during flight.

III. RESULTS

A. Force-displacement and work input

Table I shows the mean force at each compression, averaged across three different loadings. Force increases to a maximum of 7.1 N at 3.0 cm before declining slightly, which matches post-"pop" behavior after the spring section passes through the snap-through instability. Riemann sum integration of the mean curve gives us work values of 0.0142 J, 0.0566 J, 0.124 J and 0.155 J for four different compression levels (Table II). Mechanical work at full compression was $0.155 \pm 0.004\,\mathrm{J}$ (Fig. 2).

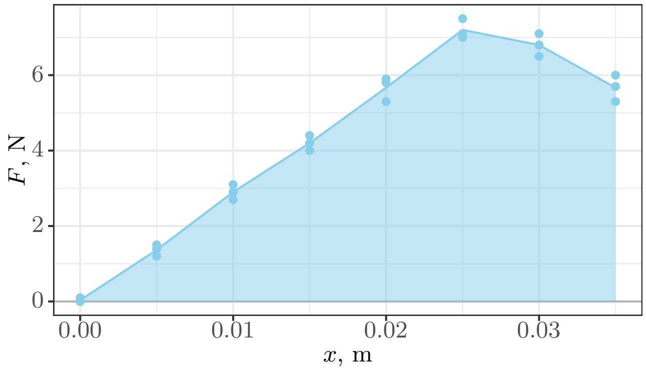

FIG. 2. Force-displacement data from Table I. The mechanical work at full compression, computed using Eq. (1) for each replicate, was 0.155 ± 0.004 J.

TABLE II. Individual trial kinematics data for launches. Values shown as mean ± sd in compact form.

x,m	v_0, m s^{-1}	h, m
0.01	1.28(2)	0.084(3)
0.02	2.66(5)	0.36(1)
0.03	3.93(8)	0.78(3)
0.04	5.00(7)	1.26(3)
0.45	5.37(9)	1.46(5)

B. Individual launch trials

Table II presents all 15 individual trials. KE and GPE are independently measured quantities.

C. Averages by compression level

Table IV summarizes the energy results by compression level. Energy loss from compression to launch (η loss) averages 46 % (Table IV). In each compression level, the three different trials are highly consistent, confirming measurement reproducibility.

A paired t-test comparing W to GPE across all 15 trials gives us $t(14) = 28.4, p < 0.0001$, confirming that the relationship between work input and launch height is statistically significant, and the null hypothesis (no relationship between work and height) is rejected.

TABLE III. Individual trial energies. Values shown as mean ± sd in compact form.

x,m	W, J	KE, J	GPE, J
0.01	0.0142	0.0047(2)	0.0047(2)
0.02	0.0566	0.0202(8)	0.0200(8)
0.03	0.124	0.044(2)	0.044(2)
0.04	0.155	0.071(2)	0.071(2)
0.45		0.082(3)	0.081(3)

TABLE IV. Mean values by compression level. Values shown as mean ± sd in compact form.

x, m	η_1	η_2	$\eta_{overall}$
0.01	0.33(1)	1.000(5)	0.33(1)
0.02	0.35(1)	0.992(1)	0.35(1)
0.03	0.36(2)	0.993(1)	0.35(1)
0.04	0.46(1)	0.9910(3)	0.46(1)
0.045		0.9920(8)	

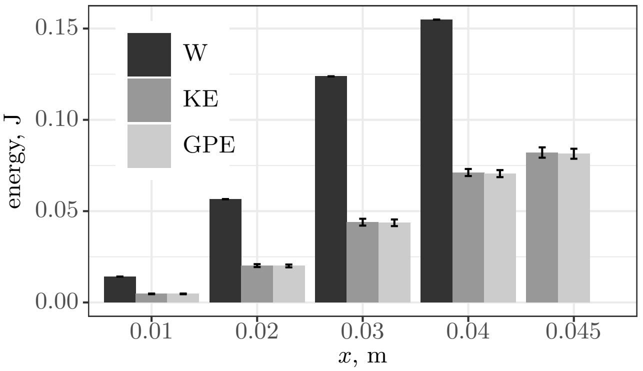

FIG. 3. Energy results by different compression levels. Data in Table III

IV. DISCUSSION

The results strongly support our hypothesis: launch height increases with work input, as do kinetic energy and maximum gravitational potential energy (Fig. 3. This confirms a robust positive correlation, not merely a trend within a single compression condition.

The mean energy efficiency $\eta = 46\,\%$ (i.e., 54 % of compression work is lost before launch) is consistent with the literature. Gent and Cho [1] report hysteresis losses of 75 % to 88 % for rapid inversion of natural rubber shells, attributing them primarily to viscoelastic internal friction during the snap-through transition [2, 7]. Arrieta *et al.* [21]report similar values for bistable polymer shells. Our observed 54 % loss is consistent with this published range, providing quantitative support for the hysteresis mechanism. Acoustic energy loss during the snap event is estimated at less than 0.5 % of input energy and is negligible relative to hysteresis.

The secondary loss from KE to GPE averaged 1 % across all trials. Our drag estimate (Section II.E) yields a predicted loss of 1 % for mid-range trials, in good agreement with observation. This confirms that the KE-to-GPE conversion loss is physically explained by aerodynamic drag and does not represent a violation of energy conservation.

The total energy budget is therefore:

$$KE = 46\,\%W, \tag{7}$$
$$GPE = 99\,\%KE, \tag{8}$$
$$GPE = 46\,\%W. \tag{9}$$

This is fully consistent with conservation of energy when all dissipative pathways are accounted for.

Several limitations should be noted. The force-displacement curve was measured quasi-statically while the actual snap-through occurs dynamically; dynamic stiffening of rubber at high strain rates could alter the effective stored energy. Additionally, Tracker video analysis introduces pixel-level uncertainty in velocity measurement, estimated at $\pm 0.5\,\mathrm{m\,s^{-1}}$, corresponding to $\pm 1\,\%$ uncertainty in KE. Future experiments could vary what the popper dimensions are and material to explore how hysteresis fraction depends on shell thickness and elastomer composition.

V. ACKNOWLEDGEMENTS

We thank the Science & Engineering Magnet Program at Manalapan High School for support. DK authored the abstract and discussion, ML performed data analysis, and RDR prepared the methods and materials and references. The manuscript was improved with input from several anonymous peer reviewers whom we thank.

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Journal of Science & Engineering **2**, 114–117 (2026)

Effect of popper condition and mass on the energy and maximum height of poppers

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(Received 30 January 2026; accepted 11 April 2026; published 17 May 2026)

Poppers are inexpensive toys consisting of a ball and spring that are able to jump; each popper has an emoji design on its face. Using poppers as a model system to examine energy conservation, this experiment investigated how their mass and design/condition affected their maximum height and total mechanical energy. We examined two poppers, differentiated by mass and design/condition (5.50 g happy vs 5.40 g sad), and ran multiple trials. We recorded the maximum height and initial velocity using video kinematics. We found that the heavier, happy popper consistently reached greater heights and had a higher initial velocity and total energy than the lighter, sad popper. Due to previous usage, mechanical warping would occur in the sad popper, illustrating the effect of the specimen's material condition on performance. We believe that specimen condition, i.e. from previous usage, is the primary factor influencing mechanical energy output rather than mass alone or emoji design, but concede our experimental design is unable to conclusively test between these alternatives.

DOI: 10.64808/jfgzkk08

I. INTRODUCTION

When an object is launched directly upwards, its energy gradually converts from kinetic to gravitational potential energy until the object reaches its maximum height. At this maximum height, the object then experiences a temporary state of rest, where the kinetic energy is fully converted to potential energy. The object then begins to drop towards the ground due to gravity, where the energy is converted into other forms of energy, like acoustic or thermal. We used the Law of Conservation of Energy [1–3], which states that energy cannot be created or destroyed but only transformed from one form to another, to compare the work done in compressing a spring with kinetic and gravitational potential energy as the spring launches and reaches its maximum height. Kinetic and gravitational potential energy were estimated from kinematics data obtained using Tracker Online [4] and methods similar to [5–10].

Poppers (Liberty Imports "Jumping Gens"; Allentown, PA) are inexpensive toys consisting of a ethylene vinyl acetate (EVA) foam ball and spring that are able to jump; each popper has an emoji design on its face. Using poppers as a model system to examine energy conservation, this experiment investigated how their mass and design/condition affected their maximum height and total mechanical energy. We examined two poppers, differentiated by mass and design/condition (5.50 g happy vs 5.40 g sad), and ran multiple trials to determine total mechanical energy and conversion efficiency. By comparing 5 trials per popper, we used statistical analysis to determine whether the observed variations in the data were significant or attributable to experimental error.

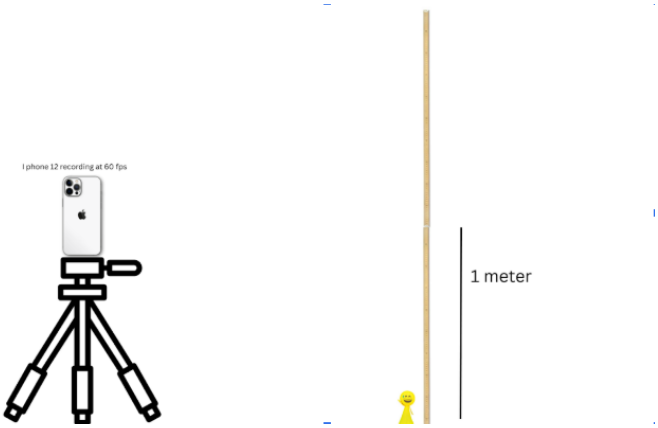

FIG. 1. Initial setup for data collection showing popper, two meter sticks, and iPhone 12 on a tripod, recording at 60 frame/s.

We hypothesized that previous usage of the popper, rather than the mass alone, would act as the primary factor determining launch velocities and max heights.

II. METHODS AND MATERIALS

A. Objects launched

As shown in Fig. 1, to measure the height (y), both sets of poppers were launched. We used two meter sticks, taped to the wall at regular intervals, stacked on top of each other, with the first touching the ground and the second directly on top of the first. The purpose of the verbal countdown before each trial was to synchronize the

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popper's release and the start of the video recording. An iPhone 12 (Apple; Cupertino, CA) was utilized to record each launch at 60 frame/s. Before the launch, the poppers' masses were recorded. The objects were released from rest at the moment the countdown reached zero, without any initial lift upwards. Each type of popper (happy, sad) was launched five times. We used frame-by-frame analysis with Tracker Online [4] to record the poppers' highest points and initial velocities.

B. Work and energy input

To determine the work done on the popper, the force and vertical displacement of the center was measured during compression. The popper was placed on a digital scale (TOP2KG; Smart Weigh; Jiangsu, China) and a scissor jack was used to controllably compress the popper by 0.005 m increments. Force was was converted from indicated mass readings in g to N using $F = mg$, where $g = 9.8\,\mathrm{m\,s^{-2}}$ [1–3].

The work was then calculated by using a trapezoidal method to numerically integrate as follows [1, 11]:

$$W = \int_0^{x_{max}} F dx. \tag{1}$$

This value represents both the work done in compressing the popper (W) and the total Elastic Potential Energy (EPE) stored in the popper before launch. This may have caused some data variations due to human error and the difficulty of perfectly centering the popper. We then tabulate the efficiency of the launch process as

$$\eta = \frac{\text{mechanical energy output}}{\text{work input}} \times 100\%. \tag{2}$$

C. Null and alternative hypotheses

We hypothesized that the emoji design should have no real impact on launch velocity or maximum height, thus the two popper designs should have equal mean launch velocities and maximum heights (H_0). Alternatively, the two popper designs could have different mean launch velocities and maximum heights (H_a).

The graphical emoji design should have neglible impact on the device performance, but confounding effects could be the mass or the usage history and physical condition of an individual popper. In retrospect, we recognize that testing a single specimen each of happy versus sad left us unable to conclusively determine whether observed differences are due to the emoji design or due to individual effects.

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

TABLE I. Sad popper initial velocity and height data for $n = 5$ replicates. $m = 0.005\,40$ kg, $v_0 = 4.65 \pm 0.05\,\mathrm{m\,s^{-1}}$, $h = 1.26 \pm 0.03$ m, KE = 0.058±0.001 J and GPE = 0.067±0.002 J.

trial	v_0, m s^{-1}	h, m
1	4.60	1.23
2	4.65	1.24
3	4.72	1.28
4	4.68	1.30
5	4.60	1.25

TABLE II. Happy popper initial velocity and height data for $n = 5$ replicates. $m = 0.005\,50$ kg, $v_0 = 5.46 \pm 0.04\,\mathrm{m\,s^{-1}}$, $h = 1.50 \pm 0.02$ m, KE = 0.082±0.001 J and GPE = 0.081±0.001 J.

trial	v_0, m s^{-1}	h, m
1	5.45	1.48
2	5.42	1.48
3	5.48	1.50
4	5.44	1.49
5	5.46	1.53

III. RESULTS

Tables I and II summarize the initial velocity and maximum height for sad and happy popper launches, respectively.

The data from Tables I and II are summarized in Fig. 2, which shows differences between happy and sad popper performance are significant (ANOVA; $p = 2.27 \times 10^{-9}$). Sad popper jumps had lower initial velocities and lower maximum heights.

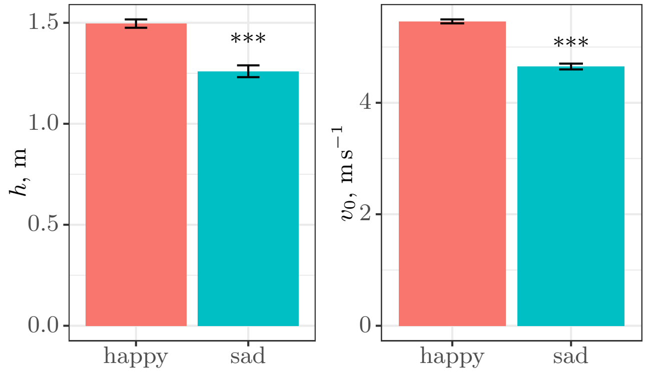

FIG. 2. Initial velocity (v_0) and height (h) data. Data from Tables I and II. For both h (ANOVA; $p = 4.39 \times 10^{-7}$) and v_0 (ANOVA; $p = 2.27 \times 10^{-9}$), differences between happy and sad poppers are significant.

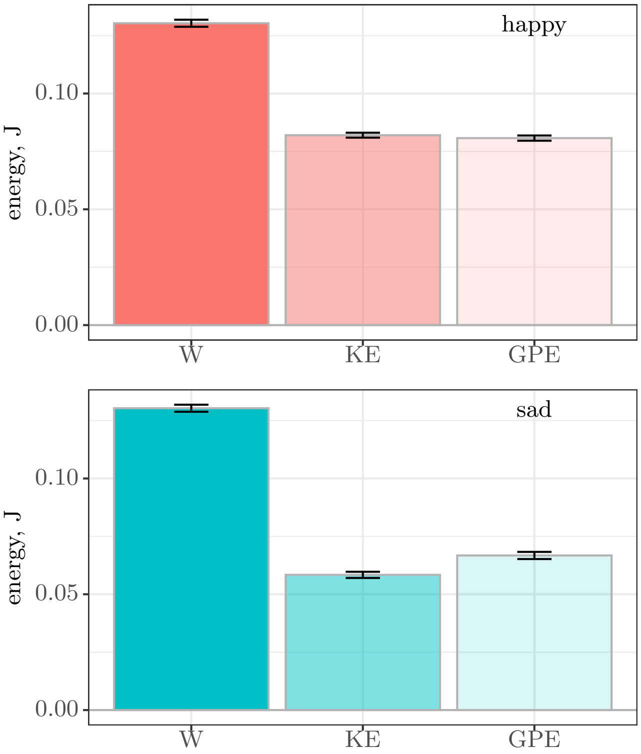

FIG. 3. Comparative energy profiles of happy (top) versus sad (bottom) poppers.

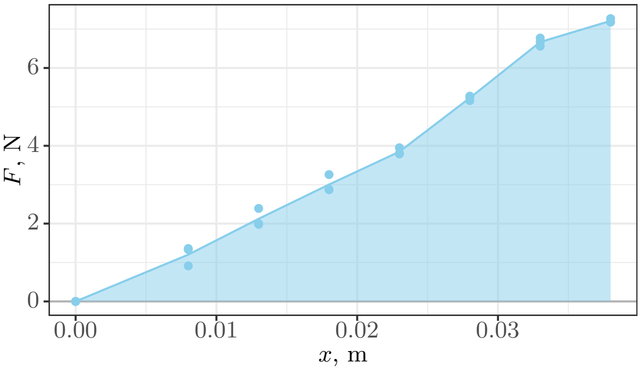

FIG. 4. Force versus displacement. The work done in compressing the popper (shaded area) is $W = 0.130 \pm 0.001$ J.

Comparison of the work done to compress (W), initial kinetic energy (KE) and maximum gravitational potential energy (GPE) are shown in Fig. 3.

The work done in compressing the popper is shown in detail in Fig. 4. At full compression, the work to compress a popper was 0.130 ± 0.001 J.

IV. DISCUSSION

A. Analysis of mass and performance

The results of this experiment indicated that the happy popper had higher maximum heights, higher initial velocities, and greater mechanical energy than the sad popper. As seen in Fig. 2, the happy popper reached an average height of 1.50 m, while the sad popper reached an average of 1.26 m. Additionally, the average initial velocity for the happy popper was $5.46\,\mathrm{m\,s^{-1}}$, compared to $4.65\,\mathrm{m\,s^{-1}}$ for the sad popper (Fig. 2).

One possibility is that there is an actual effect from the different designs, happy versus sad. Alternatively, the findings may be the result of the 0.1 g mass difference between the two specimens tested. A third possible explanation for these results is the condition of the poppers at launch. If the happy popper was was fresh out of the box while the sad popper was previously used, any previous launches of the sad popper could have resulted in plastic deformation of the EVA elastomer material, leading to lower maximum heights, low initial velocity, and lower mechanical energy. As our design of experiment only tested a single specimen each of happy versus sad popper, we are unable to further narrow down between these alternatives.

B. Energy efficiency and dissipation

By comparing the total mechanical energy to the calculated work to compress the poppers (Fig. 3), we see that the popper launch process was approximately 46 % to 63 % efficient. These efficiencies appear reasonable considering the coefficient of restitution and hysteresus of EVA foam rubber and other plastic materials, the possibility of friction in the spring section of the poppers, snap-through instability during launch. Furthermore, the relative agreement of KE and GPE in Fig. 3 suggests that air drag and losses during the flight phase are small compared to energy losses during the launch process. These observations are also in line with those reported by others in this same issue.

C. Statistical significance and experimental variables

The test confirms the statistical significance of deviations in mean initial velocity, maximum height, and launch velocity. The t-statistic of 28.9 is above the critical t-value of 2.306 for 8 degrees of freedom at $\alpha = 0.05$. We reject the null hypothesis that the two poppers have the same mean initial velocity, maximum height, and launch velocities since the p-value is significantly smaller than $\alpha = 0.05$.

Since both poppers were likely made from identical molds and materials, we feel the energy gap is best explained by prior use. If the sad popper were extensively used before testing, so that its resilience and overall structure were degraded, these would explain the observations in a way that is more convincing that the emoji design, which should have no effect, or the small mass difference due to manufacturing tolerances.

Our experimental design only used one specimen of each of happy versus sad popper designs and did not control for prior use, thus we cannot draw a definitive conclusion without further testing. We recommend using multiple specimens of each, and ensuring that they are drawn from a fresh, plastic-wrapped and sealed new box. Any future experiments should control for the popper condition by using brand-new poppers with varying mass or by measuring the spring constant (K) beforehand.

V. ACKNOWLEDGEMENTS

We thank J Komitas and the Science & Engineering Magnet Program for support. JK wrote the Introduction and performed all the equations. ES wrote the methods and materials and did the statistical analysis. LB also worked on the methods and materials and formatted all the equations. TR wrote the discussion and made the figures. We thank several anonymous reviewers, whose comments helped improve the manuscript.

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