# Analysis of energy transformation in a non-ideal spring popper

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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 $h = 1.12 \pm 0.11$ m, corresponding to gravitational potential energy (GPE) of $0.062 \pm 0.006$ 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.

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## 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]

$$W = \int F dx, \quad (1)$$

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

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

### 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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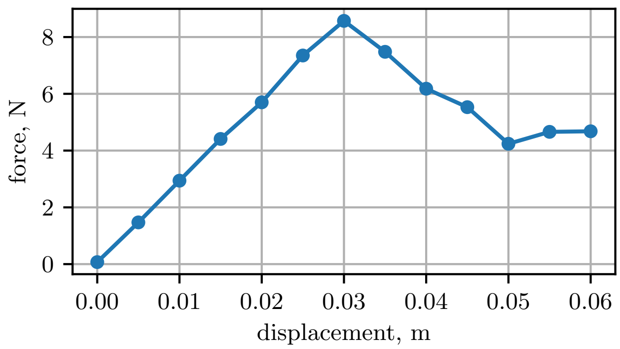


FIG. 1. Force versus displacement of the popper as it is being compressed.

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 $1.12 \pm 0.11$ m (mean ± 1 sd). Using (3) gives an estimate of the gravitational potential energy of $0.062 \pm 0.006$ 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.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004).
[2] R. A. Pelcovits and J. Farkas, *Barron's AP Physics C Premium* (Kaplan North America, Fort Lauderdale, FL, 2024).
[3] W. Moebs, S. J. Ling, and J. Sanny, *University Physics*, Vol. 1 (OpenStax, Houston, TX, 2016).
[4] A. Sendrowicz, A. O. Myhre, I. S. Yasnikov, and A. Vinogradov, Stored and dissipated energy of plastic deformation revisited from the viewpoint of dislocation kinetics modelling approach, Acta Materialia **237**, 118190 (2022).
[5] R. Larson and R. P. Hostetler, *Calculus*, 8th ed. (Brooks Cole, Pacific Grove, CA, 2005).
[6] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes in C*, 2nd ed. (Cambridge University Press, 1992).
[7] C. R. Harris, K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, J. Taylor, S. Berg, N. J. Smith, R. Kern, M. Picus, S. Hoyer, M. H. van Kerkwijk, M. Brett, A. Haldane, J. F. del Río, M. Wiebe, P. Peterson, P. Gérard-Marchant, K. Sheppard, T. Reddy, W. Weckesser, H. Abbasi, C. Gohlke, and T. E. Oliphant, Array programming with `numpy`, Nature **585**, 357 (2020).
[8] J. D. Hunter, `matplotlib`: a 2D graphics environment, Computing in Science & Engineering **9**, 90 (2007).
[9] R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria (2025).
[10] L. Rohland, Hooke's law, `https://www.ebsco.com/research-starters/law/hookes-law`, accessed 27 March 2026.
[11] D. S. Starnes, J. Tabor, D. Yates, and D. S. Moore, *The Practice of Statistics*, 5th ed. (W. H. Freeman and Company, 2015).