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Bouncing Poppers

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Toys are known to attract interest in physics and they are therefore often used in physics teaching of various topics.[1-3] The present paper deals with a simple toy, the so-called "hopper popper," which, similar to superballs,[4,5] can be used when teaching mechanics. We suggest some experiments and describe the basic physics of this toy, also providing background information for teachers.

What is a popper?

A while ago, a toy called hopper popper became popular. It is inexpensive (≈ \$2.99[6]), simple, and provides interesting physics insights in the field of mechanics. We use commercial hopper poppers, bought in a science center shop.

A hopper popper is usually made of rubber and consists of a segment of a spherical shell [Fig. 1(a)]. The segment can resemble a half spherical shell (angle from center to edges 180°) or it may be slightly smaller [angle $\alpha \approx 100°$ in Fig. 1(b)]. You may also cut a small rubber ball (e.g., a racquetball) in two halves such that each one represents a hopper popper (with 180° angle). Typical dimension of our poppers are a shell height of $H = 25$ mm, an outer diameter of $D = 55$ mm (i.e., $R \approx 27.6$ mm and $\alpha \approx 169°$), a thickness of several millimeters, and a mass around 20 g.

Left as it is, such a popper is nothing spectacular. One may drop it from a certain height and observe how it bounces back from the floor. If it falls along its symmetry axis with the spherical shape pointing downward, we observe a rebound height of around 60 cm for initial heights up to 2 m. If the initial height is, say, 30 cm above the floor, the rebound height is below 15 cm. Exactly reproducible numbers are difficult to get since the rebound sensitively depends on how the popper shell hits the floor and whether it starts rotating or only follows a linear motion.

Loading of the popper

The interesting physics starts if the popper is loaded. To do so, one exerts a force on the shell such that it bulges inward. Depending on the rubber material (its elastic properties) and the geometry (radius of curvature and shell thickness), one can observe that the material behaves in a bistable manner, i.e., if bulged inward the shell stays in this position for several seconds if left unperturbed. For our popper, the center part of the shell, forming the tip of the bulged form, moved between 40 to 45 mm!

The force needed to invert the popper shape can be quite high—occasionally more than 100 N. Detailed investigations[7] have reported force-versus-distortion profiles, which at the beginning are nearly linear (Fig. 3). If therefore treated as a simplified system with linear restoring force, initial force constants averaging around 2500 N/m with a maximum of about 7000 N/m (slopes of broken lines in Fig. 3) were found.

These numbers may seem astonishingly large. However, measure the force by putting a load on top and see how little the popper bulges inward. You may be surprised how easy it is to create such large forces with your hands (small children may, however, not be able to do so). The trick is to use

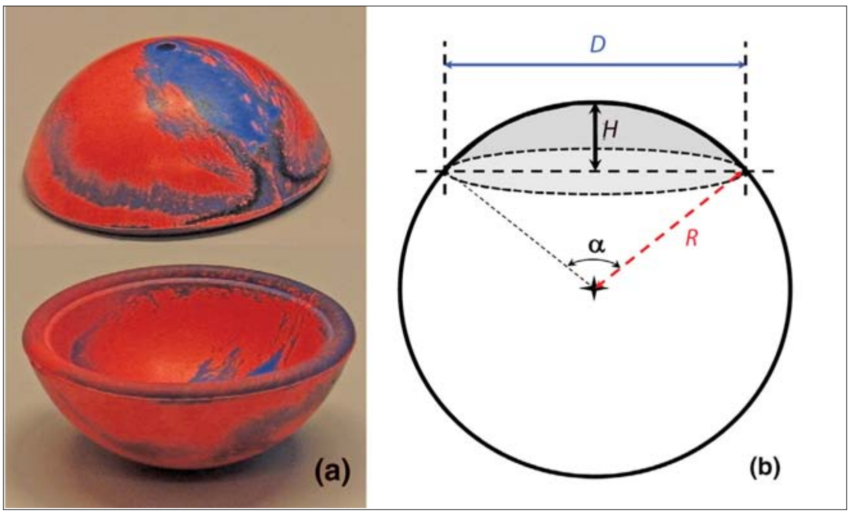

Fig. 1. A hopper popper is part of a rubber spherical shell (a). The shell section may be characterized by its angle α, curvature radius *R*, shell height *H*, and shell diameter *D*, which are related to each other via simple trigonometry (b).

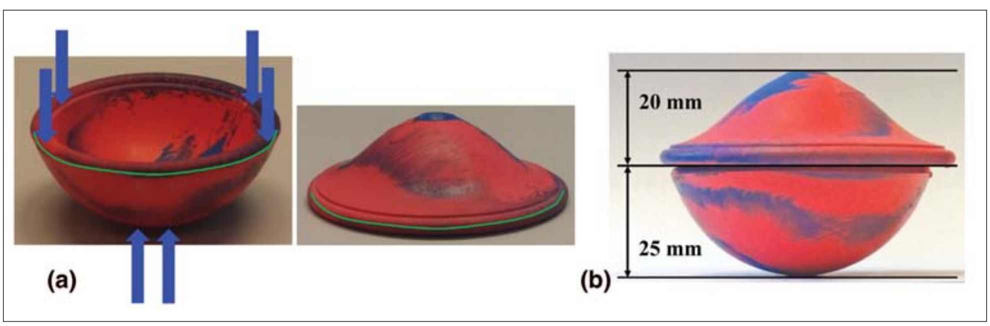

Fig. 2. (a) Loading of the hopper popper is best done by using both hands. The thumbs apply pressure from below while middle and index fingers do so from above (arrows). Thereby the form quickly flips into the inverted geometry form. The green line in both cases indicates more or less the same part of the shell. Loading with a single hand is much more difficult and does not work easily. (b) A loaded popper on top of an unloaded one, indicating the associated shell distances between the two cases.

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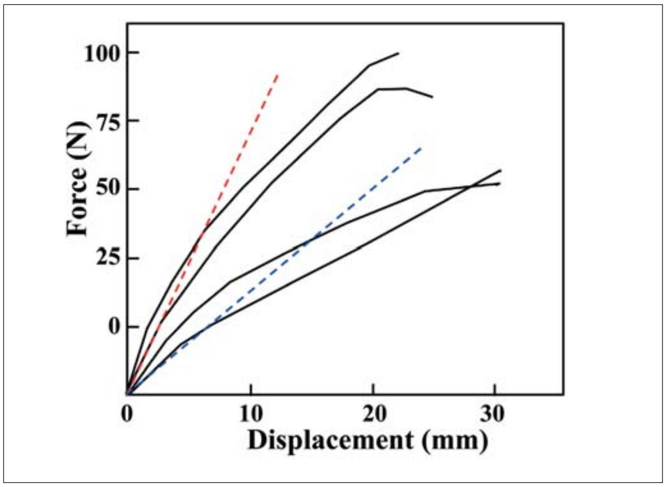

Fig. 3. Forces needed to establish certain displacements upon loading of various types of poppers (after Ref. 7). As an example, two lines with slopes corresponding to about 2500 N/m and 7000 N/m have been added as broken lines.

both hands: use the two thumbs to press from the bottom while simultaneously holding the shell with two index and two middle fingers from the top (Fig. 2). Thus the fingers exert a torque that simplifies loading. Trying to load by just pressing with one or two thumbs on the shell while the popper lies on the floor is much more difficult (if not impossible for most people).

The amount of time the popper stays in the inverted state can be lengthened by drilling a small hole in the center [see Fig. 1(a)]. These so-called "dropper poppers" are the standard poppers commonly sold in science centers around the world. The hole is important for the bistability of the popper. Upon inversion, the rubber around the hole stretches radially, which allows the rubber to relax, enhancing its stability,[7] i.e., lengthening the time the popper stays in the inverted shape.

In addition to just waiting, the flip back of the inverted popper into its original shell shape can be induced mechanically, for example, by letting the popper drop to the floor with the inverted part pointing upward. Once it hits the floor the toy (usually) returns to its original shape immediately (our experience is that only a few poppers lose their elastic properties and do not pop at all).

The fun starts

Whatever option is chosen, putting the inverted form on a table or the floor and waiting (when will it happen?) or letting it drop to the floor (it happens upon contact), one can always observe the same phenomenon: the shell very quickly returns to its initial shape. While doing so, the back switching shell exerts a force on the floor and the reaction force propels the popper high into the air (see video #1 at *TPT Online*, http://dx.doi.org/10.1119/1.4933153_1). Figures 4 and 5 show some snapshots from high-speed video sequences used for analyzing the initial motion. Our popper could easily reach heights above 2.20 m, with a maximum height of around 2.5 m, for both setups, first for inverted poppers resting on the floor and second after dropping them from a certain height onto the floor. Height was measured with a meterstick by a person standing on a chair such that eye height was at the position of measured height. The achievable height is nearly independent on dropping height. Ten attempts with a loaded popper resting initially at the floor led to an average height of (2.27 ± 0.05) m. The independence of dropping height indicates that the rebound energy is mostly due to the stored poten-

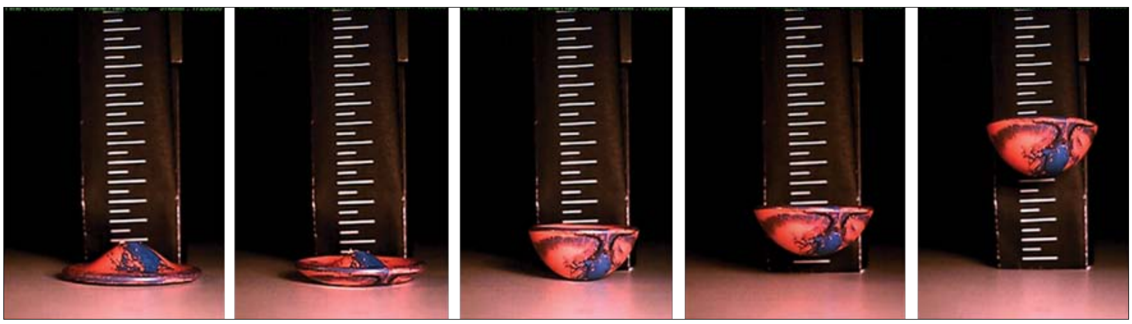

Fig. 4. Snapshots from high-speed video (4000 fps, integration time 1/20,000 s) of start of a popper while resting on floor. Relative times: 0 ms, 3.5 ms, 5.5 ms, 7 ms, and 12 ms. Readers can view video #2 at *TPT Online* at http://dx.doi.org/10.1119/1.4933153_2.

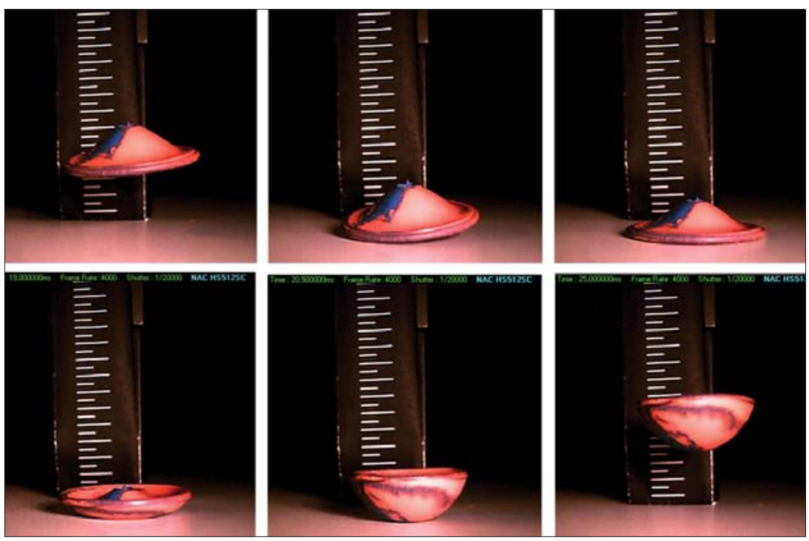

Fig. 5. Snapshots from high-speed video (4000 fps, integration time 1/20,000 s) of start of a popper after falling to floor. Relative times: 0 ms, 11.75 ms, 15.50 ms, 19.00 ms, 20.50 ms, and 25 ms. Readers can view video #3 at *TPT Online* at http://dx.doi.org/10.1119/1.4933153_3.

tial energy. As a matter of fact, some poppers do invert with time delay. They hit the floor with more or less no rebound. In a second step they jump back upon shape inversion. This means that the initial potential energy due to their falling height is transferred into heat before the popper inversion takes place. This reasoning is also supported by the fact that loaded poppers starting from rest do reach similar heights.

Some energy considerations

One may approach the problem from various sides. First let us consider the stored internal energy by considering the popper in a very simplified model as a compressed spring with known average spring constant of 2500 N/m. Knowing that the center part of the shell moves up around x =25 mm (depending on popper) while switching back, we can estimate the stored potential energy

$$E_{\text{pot}} = \frac{1}{2}kx^2$$

to be as large as 0.5 J. Even if force constants for our poppers differ from the ones in Fig. 3, we expect the same order of magnitude, i.e., the stored potential energy should be between 0.1 to 1 J.

Second, we measure the initial velocity right after the rebound (or start) from the high-speed recordings. For this purpose, we could use the known dimension of the popper. In addition, a scale has been added with a distance of 1 cm between two adjacent long lines and shorter lines in their middle. From both scales we find initial velocities of around 7.3 ± 0.3 m/s. This gives an initial kinetic energy of around

$$E_{\text{kin}} = \frac{1}{2}mv^2 \approx (0.53 \pm 0.04)\ \text{J},$$

which is consistent with the spring potential energy.

Third, the high-speed recording shows that the period of flipping between states lasts 4–5 ms (the 4 ms was observed when dropping the popper, the longer 5 ms for start at rest may be partially due to the fact that the start of the movement was more difficult to detect). Using the velocity change of 7.3 m/s from rest and the 5-ms period, we can estimate the acceleration of the popper due to the flipping to be around 1.5×10^3 m/s^2. This acceleration, together with the popper mass of 20 g, results in a force $F = ma$ of around 29 N. The work exerted by this force for the distance of about 20 mm, which is the effective length during which the force acts while bulging outward, amounts again to $W = Fs =$ 0.58 J.

Fourth, from the measured height of 2.27 m of the flying popper (initially at rest), we can estimate the potential energy it gained in the field of gravity to be $E_{\text{pot}} = mgh \approx 0.44$ J. For many experiments this value is consistently smaller than the one expected from the three estimates from above.

The influence of drag

The initial velocity of 7.3 ± 0.3 m/s would yield a maximum height—without friction—of around 2.72 ± 0.22 m (from $mgh = ½\, mv^2$). We want to check whether the difference in observed mean height of around 0.45 m can be due to air resistance. While moving upward, the spherical segment suffers from frictional forces in the air, which may be described by

$$F_{\text{friction}} = \frac{1}{2}c_{\text{D}}\rho A v^2,$$

where ρ is the density of the air, A is the cross-sectional area, and c_{D} the drag coefficient, which depends on geometry. For half spheres with opening toward the relative air movement, c_{D} easily exceeds a value of 1.3 for large Reynolds numbers Re ($Re = \rho\, vl/\eta$, with $\rho \approx 1.3$ kg/m^3: density of air; l = 55 mm: object dimension, here popper diameter, $\eta \approx 1.7 \times 10^{-5}$ m/s^2: viscosity of air).

Starting with initial upward velocity v = 7.3 m/s and using area and mass of popper, density of air, and a value c_{D} = 1.3 (i.e., treating the popper as a closed half-sphere), we numerically integrated the equation of motion iteratively using an Excel spreadsheet program. As a result, the maximum height of the popper with friction would be 2.17 m, i.e. 48 cm less than without friction. Obviously this approximation for drag is already a quite good first order description of the process. Possible reasons for the remaining discrepancy are that the popper c_{D} value is unknown and may differ appreciably from 1.3. First, the popper is not a hemisphere. Second, we only have poppers with holes in the center, which will definitely lead to changes of the airflow around the popper and hence also change the drag coefficient.

Due to the associated uncertainties in drag coefficient, it may well be that there is also an additional source for energy loss of the popper upon rebound. As a matter of fact, one can observe that the popper usually starts to oscillate. Before discussing these oscillations, however, we want to test whether our description of drag is correct at all in order to explain observed height differences. For this purpose a slightly modified experiment was performed.

Testing the drag model: Start from rest with ball on top

We placed a small ball on top of the loaded popper (this was easily possible due to the hole in the center of the popper when we start initially at rest) (Fig. 6). The idea was that upon rebound the ball would be accelerated, and from the initial velocity of the ball and the well-known c_{D} value of a sphere in air, a quantitative comparison of the involved energies could be made. Since the ball was not changing its shape as much as did the popper, we anticipated that shape oscillations would not contribute very much, i.e., drag alone should be sufficient to explain the experiment.

The process in itself was surprising although expected at second glance. Figure 7 depicts some snapshots from a high-speed video sequence. While the popper inverts its form, the supporting part around the hole retreats very rapidly, leaving the ball in mid-air and starting a free fall. The time it takes for the popper inversion is 5 ms. Then the time before the lower part of the popper reaches again the original ball height of about 2 cm above ground gives another 2.5 ms. Within this maximum time of 7.5 ms when the ball is unsupported, it can only fall a distance of less than 0.3 mm, i.e., it looks like the

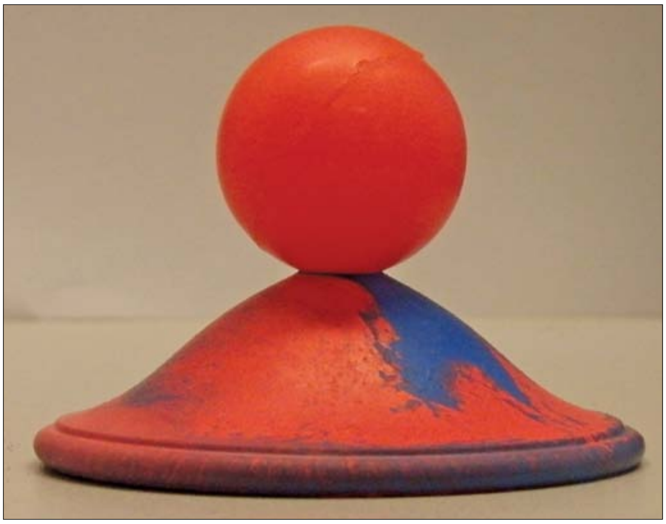

Fig. 6. Loaded popper with a small ball (mass 9.1 g, diameter 26 mm) resting on top (on the shallow pit due to the center hole).

ball stays in mid-air before being hit by the upward moving popper. It is not easy to analyze the collision in detail since it is inelastic, as can be seen from the lower part of the popper. During the collision, it is appreciably extended [Fig. 7(b)], which initiates some popper shape oscillation. Furthermore, the popper also starts to rotate after the collision.

We start the analysis by measuring the initial ball velocity. We did this by first using the scale behind the ball and second by using the known ball diameter. In both cases we found directly after the collision $v = 8.0 \pm 0.1$ m/s. Without friction, this vertical velocity should lead to a maximum height above ground of 3.26 ± 0.08 m. We measured the maximum height by measuring the distance from our ceiling (3.51 m) to be about 3.20 ± 0.10 m, i.e., slightly lower than the value expected without friction. Using the Excel spreadsheet program, we again numerically integrated the equation of motion for $v_{\text{start}} = 8$ m/s using the frictional force

$$F_{\text{friction}} = \frac{1}{2} c_{\text{D}} \rho A v^2$$

with a drag coefficient $c_{\text{D}} = 0.3$, which is nearly constant for Reynolds numbers *Re* between 10^3 and 10^5. (This *Re* regime means that the drag coefficient in our experiment is almost constant for velocities between sphere and air of between 0.5 m/s and 50 m/s. c_{D} slightly increases for lower velocities; however, since frictional effects are small anyhow and the height for a start velocity of 0.5 m/s is only 1.3 cm without friction, we assume the same constant coefficient also for the velocities between 0 and 0.5 m/s.) The numerical result gives a maximum height with friction of 3.15 m, i.e., about 11 cm less than without friction. This is consistent within error bars with the experimental result. Therefore we believe that the drag model is correct.

Popper oscillations and heat transfer to floor

Finally we want to discuss additional energies associated with poppers. The collision of a falling popper with the floor is inelastic, i.e., the floor as well as the popper should heat up. Also, a loaded popper at rest does not transfer all of its stored potential energy into kinetic energy as discussed above. The rapid form inversion process leading to the lift-off of the popper resembles again an inelastic collision of the popper with the floor. As a consequence, part of the initial potential energy of the popper is transferred into heat, i.e., popper as well as surface are again expected to slightly warm up in a transient process. This should be observable, similar to the effect of a collision of a tennis ball with a surface.[9] For tennis balls bouncing from the floor, the amount of energy transferred into heat can easily amount to more than 75%.[4] For poppers that fall from a certain height before rebounding, the available potential energy is again of the order of several joules. For loaded poppers, initially at rest, quantitative estimates are more difficult since the exact amount of stored internal potential energy is not known. However, even if only 20% of the initial energy (of the order of 0.1 J) would end up to heat popper and floor, this may also be detectable with sensitive instruments.

Due to the geometry of the popper, our initial expectation was that the floor should heat up homogeneously within a circular area defined by the diameter of the popper. Surprisingly, the heat transfer to the floor—as measured with a high-speed infrared camera—happened in a multi-ring-like manner (Fig. 8), with maximum temperature rises of around 1 K. This implies what could also be partially observed in the high-speed videos—that the inversion involves some oscillations, i.e., the geometry change into the hemispherical shape does not happen in a single smooth transition. At a given time at the beginning of the process when the outer part of the form inverts, an outer ring segment hits the floor

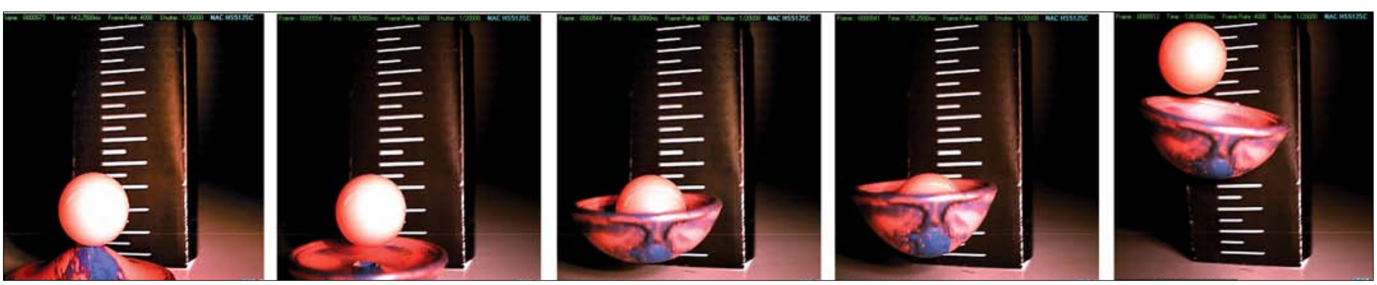

Fig. 7. Snapshots from high-speed video (4000 fps, integration time 1/20,000 s) of start of a popper initially resting loaded on the floor while supporting a small ball. Relative times: 0 ms, 4.75 ms, 7.25 ms, 8.00 ms, and 15.25 ms. Readers can view video #4 at *TPT Online* at http://dx.doi.org/10.1119/1.4933153_4.

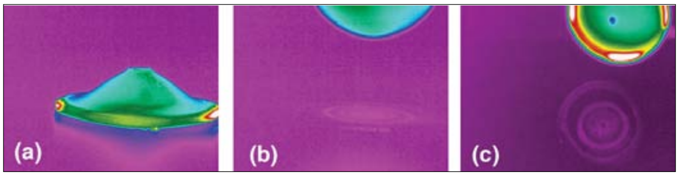

Fig. 8. Snapshots from high-speed IR videos (SC 6000 MW IR camera, operated at 430 Hz). The color scale refers to raw signals, which relate to temperature. (a) and (b) Side view at touch down and after retreating from the floor. (c) Top view to better visualize the ring-like structure of the heat transfer during the collision. Readers can view video #5 at *TPT Online* at http://dx.doi.org/10.1119/1.4933153_5.

and transfers heat. Due to the collision, form oscillations start within the popper. As a result, adjacent parts of the shell to those that just touched the floor will oscillate back from the floor and have no contact. Rather a more distant next ring-like part of the shell will touch the ground next. The same can happen a few times, resulting overall in the observed ring-like structure rather than a homogeneously heated circular area. Note that the images in Fig. 8 refer to raw signals. Temperatures are of the order of 1 K, but change rapidly.

The shape oscillations were to be expected because poppers suffer from an extreme shape change. The outer diameter in the loaded popper is about 65 mm, whereas it only amounts to 55 mm in the relaxed geometry. Therefore, shape oscillations with amplitudes of several millimeters are possible. In the simplest model, the potential energy in a spring oscillation is ½ kx^2. Assuming $k = 2500$ N/m (or 7000 N/m) and $x = 6$ mm, we find for example 0.045 J (or 0.126 J), i.e. a total energy in the oscillation of 0.09 J (or 0.25 J).

Conclusion

We have reported experiments and basic physics concepts behind hopper poppers, simple and well-known popular toys that lead to a lot of fun. In addition, some additional background information for teachers was given.

If disregarding transient heat transfer and shape oscillations upon rebound, the underlying physics of poppers is mostly simple such that this toy may provide an alternative approach to teach the subjects of kinetic and potential energy and vertical throws.

And what to do next? Teachers and/or students may find more interesting things to do with poppers. We give one example: it is also possible to put the loaded popper on top of an inclined plane (angles of up to 30° are possible without slipping of the popper). When inverting its shape, the popper starts a movement as if thrown at an angle, i.e., poppers may be used to study two-dimensional throws.

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