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Article

Analyzing the effects of multiple adhesives on elastic collisions and energy loss in a Newton's Cradle

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SUMMARY

The energy conservation in a system of objects in collision depends on the elasticity of the objects and environmental factors such as air resistance. One system that relies heavily on elasticity is the Newton's Cradle. The elasticity of the spheres is what allows prolonged movement, but these spheres also excessively collide, causing more energy to be lost. Were an adhesive to be added to these spheres, then the elasticity would decrease, and so too would the chaotic movements that cause loss of energy. We aimed to determine the extent to which these adhesives serve to mitigate or worsen the chaotic movements and elastic collisions. Knowing the extent to which adhesives may mitigate radical interactions could allow for the building of more efficient procedures reliant upon elastic collisions, such as an elastic and inelastic collision apparatuses. We hypothesized that for all tested types/levels of adhesives, the final sphere would travel a shorter distance than the control. We also hypothesized that the rate at which the distance traveled decreased would increase as more adhesives were added. Although the maximum distance reached for all trials with adhesives was less than the control, each adhesive type varied in its effect on how the maximum distance reached changed. Results also varied pertaining to the correlation between the layers of adhesives and decreased rate of swings. Our findings display complex effects of multiple adhesives on elasticity and confounding movements within a system that relies heavily upon these characteristics to perpetuate motion in the system.

INTRODUCTION

The usage of a Newton's Cradle is simple: one pulls back the primary sphere to a set length, then, with the release of the sphere, gravity carries it toward the string of other spheres in a line. Within a closed system, momentum must always be conserved, and steel, as a very elastic substance, can cause near-elastic collisions. When two different objects collide and no energy is lost within the system, such an occurrence can be referred to as an entirely elastic collision (1). This means the final sphere reaches the approximate initial distance of the primary sphere before becoming subject to the force of gravity and falling back into the line of other spheres (2). Were the Newton's Cradle a closed system (a system where no outside factors that cause energy to dissipate over time are involved) then the motion of the spheres would continue forever. The Newton's Cradle is not a closed system, however, and factors such as chaotic sphere movement, heat, sound, air resistance, and string vibration lead to a Newton's Cradle eventually losing all the input energy and therefore stopping movement. Also, since the spheres are made of steel, an additional loss of energy occurs in the system over time, leading to a decrease in the distance the final sphere travels until it eventually comes to a full stop (3). The spheres on a Newton's Cradle attempt to replicate a perfectly elastic collision by utilizing steel as the substance material (4).

Adhesives are known for their ability to stick two separate objects together through a combination of van der Waals and mechanical forces (5,6). When adhesives are applied to a system such as a Newton's Cradle, they cause the entire system to be less elastic, because adhesives are by nature much less elastic than steel. Yet, the ability of adhesives to stick certain spheres together can potentially limit variables that influence the elasticity of a system. One of those variables is chaotic motion, where a sphere on one end collides with the main body of spheres and then the end sphere is repulsed a small amount due to the imperfect elasticity of the material. Chaotic motion then causes a smaller collision that leads to unintended increased movement of strings and spheres, leading to an overall energy loss in the system. Adhesives allow for less unintended movement of the spheres as they force them to be connected to each other rather than collide with one another.

The elasticity of the materials involved in the bodies of motion of a Newton's Cradle is commonly hard to determine. Studies have shown that when attempting to determine how different materials affect the elasticity of collisions within the cradle, many are unable to predict the degree of inelasticity of materials such as wood or rock compared to the degree of inelasticity of steel (7). Even when steel is utilized in a Newton's Cradle, it is often difficult to determine just how much energy will be lost in the system due to confounding variables such as air resistance and string vibrations. These situations require the assistance of a digital tracker to improve prediction accuracy (8). Previous work suggests that the elasticity of a substance is not something that can be simply approximated to any influential degree and that in-depth studies are required to determine how certain materials in systems as many-bodied as a Newton's Cradle affect the elasticity of collisions and therefore maintenance of energy (7,8). Estimates tend to predict a higher amount of elasticity from non-steel material than there is (7,8). Based on these reports, we anticipated that biased perspective may cause us to believe adhesives are closer to steel in elasticity than they truly are, when in reality adhesives must have a highly mitigating effect on the elasticity of steel.

We hypothesized that for both adhesives applied within the experiment, chewing gum and duct tape, there would

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be a marked decrease in the overall movement of the final sphere within the system. We also hypothesized that as more adhesives are applied, there would be a lowered rate of change with each consecutive swing, so that each swing within a trial travels close to the same amount of distance as the primary swing. The decreased travel distance is due to more spheres being combined and therefore unable to interact with each other in unintended ways. In reality, the decline in elasticity of the collisions was apparent for each trial that utilized adhesives, however the change in rates was unique for each type of adhesive utilized, and we observed interesting phenomena for each trial as well. Such interesting phenomena included when the tape failed to couple spheres despite its supposed strength, and when the gum trials maintained energy in the system better than the tape. This study was conducted in order to better understand the effects that adhesives could mitigate radical interactions. This understanding is important as it could allow for the more effective building of procedures that rely upon elastic collisions, such as with the performance of a ball and clay experiment, which allows for a display of the change in collision types of objects with different heights and sizes.

RESULTS

We selected two adhesives with different properties: chewing gum and duct tape. The gum was chosen for its relatively weak adhesiveness and cushiony structure. Therefore, gum was meant to test the effects of a weak adhesive on elastic collisions. Gum has a Young's Modulus value ranging from 0.8 to 2.06 MPa, making gum highly inelastic (9). Its adhesiveness is due to the presence of polyvinyl acetate; however, due to the low percentage of polyvinyl acetate, the overall adhesiveness of the chewing gum is relatively low (10,11). We hypothesized that gum would show no extreme ability to mitigate unwanted sphere movement as its low adhesiveness would cause spheres to become more easily uncoupled from the gum and, therefore, cause more unanticipated collisions compared to stronger adhesives such as tape. We also hypothesized that gum would increase the inelasticity of the collisions due to gum being less elastic of steel. Gum was applied by taking half a stick of chewing gum, placing it under water, and then attaching it to the face of the utilized spheres.

The other adhesive tested was duct tape, which was meant to test conflicting phenomena that may arise when a pressure-sensitive adhesive bound by solid film is used (12). Duct tape has a Young's Modulus value of 10.1 MPa, which is greater than that of gum yet distinct from steel, which is approximately 200 GPa (13). Duct tape's adhesiveness is caused by the coating of rubber-based, pressure-sensitive adhesives(14,15). The duct tape was applied by taking a small square of duct tape, folding it in on itself so that the adhesives faced both ways, then attaching one side to the face of an applied sphere.

In our experiments, we placed a measuring device parallel to the row of spheres and then recorded the activity from a vantage point perpendicular to the row of spheres (**Figure 1**). In this orientation, a review of the footage would reveal the horizontal displacement of the final sphere from its row, measured in centimeters. The treatments were an application of each adhesive type to the primary sphere (the sphere being pulled back), then another layer of the adhesive was

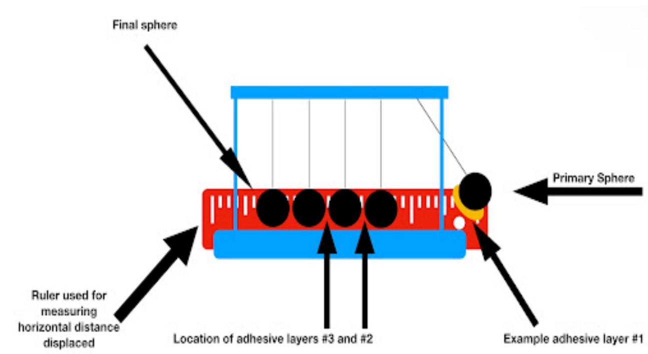

Figure 1: Experimental setup. The primary sphere is the one pulled back by hand for each trial and is the location of the first layer of adhesive. The sphere closest in proximity to the primary sphere receives the second layer of adhesive and so forth. The final sphere's displacement is measured horizontally in centimeters. This image has been modeled from the point of view of the camera utilized to measure maximum horizontal displacement for each swing.

added to the sphere in front until three layers have been added for each adhesive (**Figure 1**). This setup results in three wrapped spheres with one adhesive layer attached to each of them. So, for a two-layer treatment, an adhesive would be placed on the primary sphere (where it would be assumed to couple with the secondary sphere) and between the secondary and tertiary spheres. Similarly, with the three-layer treatment, another adhesive would be present between the tertiary and quaternary spheres. These configurations led to six treatments plus a control (no adhesives applied). We calculated the average horizontal displacement and average decrease between swings from ten trials for each of the six conditions we tested.

The final sphere of the control reached an average distance of 7.2 cm, with an average decrease in distance of 0.3 cm (**Table 1, 2**). This was the highest average distance reached and the highest average decrease in distance found within the entire experiment.

The gum treatment with one layer reached a maximum average distance of 2.0 cm (**Table 1**). Yet, this treatment was much slower to decrease in distance traveled (**Table 2**). The energy lost within the system is seen to grow at a statistically significant rate between the one-layer and two-layer treatments and the two-layer and three-layer treatments (p-value < 0.01, p-value < 0.0001) (**Figure 2**). All treatments for gum lost far more energy than that of the control (p-value

Distance traveled for each Swing # (cm)	Control	1 Layer Gum	2 Layer Gum	3 Layer Gum	1 Layer Tape	2 Layer Tape	3 Layer Tape
Swing 1	7.2±0.12	2.0±0.17	2.0±0.10	1.7±0.08	2.0±0.07	1.6±0.05	1.9±0.05
Swing 2	6.9±0.17	2.0±0.13	1.9±0.09	1.6±0.08	1.7±0.06	1.5±0.05	1.6±0.06
Swing 3	6.7±0.19	1.9±0.10	1.8±0.07	1.5±0.07	1.6±0.06	1.4±0.05	1.5±0.06
Swing 4	6.4±0.18	1.8±0.10	1.7±0.06	1.4±0.07	1.5±0.07	1.2±0.05	1.4±0.07
Swing 5	6.2±0.31	1.8±0.12	1.7±0.06	1.4±0.07	1.4±0.07	1.1±0.06	1.3±0.07

Table 1: Average distance traveled by final sphere for the first five swings of a Newton's Cradle pendulum. The mean distance traveled in centimeters under each of the first five swings for every treatment (n = 10).

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	Control	1 Layer Gum	2 Layer Gum	3 Layer Gum	1 Layer Tape	2 Layer Tape	3 Layer Tape
Average Decrease in distance reached (cm)	0.3±0.07	0.1±0.07	0.1±0.06	0.1±0.06	0.2±0.11	0.1±0.06	0.2±0.11

Table 2: Average decrease in the distance reached by the final sphere between each of the first five swings of a Newton's Cradle Pendulum. The average decrease in the distance reached between each of the five swings recorded for every treatment tested (n = 4). The values were calculated by subtracting the average distance reached by the first swing from the second, the second from the third, the third from the fourth, and the fourth from the fifth. The average was found from this sample of four.

< 0.0001, p-value < 0.0001, p-value < 0.0001).

The results from the tape layers were similar to the gum in their notable effect on the elasticity of the system, with only one layer bringing the maximum average distance down to 2.0 cm (**Table 1**). The tape treatments almost always lost more energy than gum for each layer treatment (p-value < 0.0001, p-value < 0.0001) except for the three-layer treatments (p-value > 0.05) (**Figure 2**). A very interesting phenomenon can be observed within the tape treatments as an increase in layers led to first a decrease in the average distance, then an increase, with large differences in the average distance reached found within the first two swings. The transcribed energy loss obviously mimics this, as the highest loss in energy is found in the two-layer treatment, the second highest in the three-layer treatment, and the lowest energy loss is found in the one-layer treatment (**Figure 2**). These values are all statistically significant from one another and the control (t(9)=14.21, p<0.0001; t(9) = 10.20, p-value < 0.0001; t(9) = 4.01, p-value < 0.001; t(9) = 34.80, p-value < 0.0001; t(9) = 39.24, p-value < 0.0001; t(9) = 36.18, p-value < 0.0001). The tape had an average decrease in distance

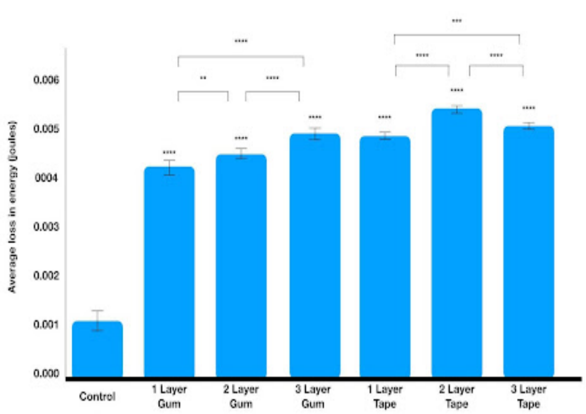

Figure 2: Average loss of energy in the Newton's Cradle within five swings under all treatments. The initial energy as the primary sphere first collides with the secondary sphere, the final energy as the fifth swing converts its maximum potential energy into kinetic energy as it swings past its original resting place, and the difference between the two (n= 10). Found by converting mass and displacement into joules utilizing various equations (can be found in the methods section). p-value < 0.0001 is shown as ****, p-value < 0.001 is shown as ***, and p-value < 0.01 is shown as **. Asterisks above the error bars indicate significance relative to the control, and asterisks above the floating bars indicate significance between the indicated layers of each adhesive type.

similar in its distribution to the average distance reached, with the rate of motion decreasing from the one-layer to the two-layer treatment, then increasing from the two-layer to the three-layer treatment (**Table 2**).

DISCUSSION

The purpose of this study was to determine the effects of adhesives on energy loss within a Newton's Cradle. We hypothesized that although the motion that the final sphere traveled would decrease compared to the control per each layer of adhesive applied, the maximum distance reached by the sphere each trial would decrease less with each swing. The results from this experiment showed that both adhesives tested had high effects on the elasticity of the collisions in Newton's Cradle. These effects include shortening of the average distance traveled. We also observed that additional layers changed the effects the adhesive had on the average distance the final sphere reached (and therefore the energy the system lost). These changes were a direct decrease in distance reached with each layer in the gum trials and a decrease then an increase in the tape trials. The experiment contradicts much of the hypothesis and displays the idea that adhesives in a Newton's Cradle are much more complex than previously assumed.

The gum experiments supported the hypothesis, where increased layers led to a decrease in movement and energy due to inelastic collisions. What defied expectations was the fact that an increase in gum layers produced no change in the average decrease in distance reached. The movement of the spheres with even one layer of gum was drastically different from the typical movement of a Newton's Cradle. The presence of the gum altered the primary sphere's striking ability so that the final sphere was not displaced separately from the rest, but instead, all spheres in the chain moved together. This means that more layers of gum did not affect the variability in sphere movement by combining spheres into one body, as all the spheres were already moving together, even with only one layer of gum. The increased layers of gum, therefore, were unable to exert any change upon the average decrease in distance traveled as the anticipated effect was already occurring, and the addition of more layers only served to allow for a higher loss of energy within the system. The lower average decrease in the distance reached for all layers of gum is believed to be due to the decreased distance traveled. With less distance traveled, there is less time in which gravity centripetally acts upon the displaced spheres. The spheres' velocity is not accelerated enough to cause significant energy to be generated so that high amounts of chaotic movement (such as string vibration or excess collisions) occur. Although less energy is being generated with each swing, there is also less energy removed from the system per swing, causing the average decrease in distance to be low. The tape, like the gum, was able to remove a lot of the motion from the system. However, the results from the tape are highly different from what we expected. For example, the two-layer trial had a lower average distance reached and average decrease in distance than the other two treatments under this adhesive. Unlike the gum, the adhesive layer of tape was so thin that the speed at which a collision occurred between the primary and secondary sphere was able to cause the point of contact to push through the adhesive layer and instead interact mostly with the non-adhesive film (**Figure 3**). This

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Figure 3: Image of spheres from 1 layer tape trial. The minimal separation of the body of spheres observed despite the presence of tape.

behavior caused the primary and secondary spheres not to couple for most collisions until energy was removed from the system to such a degree that the slowed movement allowed for bonding. Spheres connected by tape also usually moved separately from spheres not coupled by tape until sufficient energy was removed from the system. This phenomenon is most likely due to differences in mass contained within the body and how energy travels through the intermediaries of that mass. These factors cause a high degree of energy loss within the tape treatments due to many different interactions between various separate bodies of spheres. Energy loss is most evident in the two-layer treatment, where the primary sphere was moving independently due to its high speed causing it to not couple, the secondary and tertiary spheres moving independently as they are connected by tape, and the quaternary and quinary spheres move independently as well (as they were the only spheres untouched by tape). Although, these final two spheres are not coupled, so increased radical movement occurred between the two. Overall, the sum of these behaviors caused the two-layer tape treatment to travel the least distance and therefore lose the most energy within the experiment due to the high degree of radical movement and string vibration caused by the chaotic conditions brought on by the tape.

We did not test these related theories in this study, which sought only to test two variables: lack of elasticity and mitigation of energy loss. Our study did not account for the unique motions within the system that come from the combination of the two variables tested. Thus, due to the limitations of this experiment, we cannot identify the exact causes for the differing behavior within each treatment. However, the proposed theories have all been modeled after the idea that the degree of adhesive abilities and mitigation of elasticity in collisions was at the heart of all strange behavior noted.

In a future experiment, the reduction of spheres within the Newton's Cradle system to only two would help to better determine the effects of adhesives within the system. This is because it would lower the unanticipated sphere groupings that occurred in the completed experiment. This experiment would only include one layer, but the differences noted in separate adhesive elasticity would be more reliable as interactions between the untreated spheres would be eliminated. Additionally, more layers of adhesives on all the different spheres of the Newton's Cradle could be tested. Instead of being centered around determining the energy lost given certain scenarios, the experiment could then focus on what adhesive types and placement locations allow for the least and most energy conservation. This setup would build on our work and provide additional insight into the best possible utilization of adhesives with elastic collisions in a machine.

Our results differ largely from the concepts of tape and gum's modulus and adhesive power in previous literature (9,10,13,15). The idea that duct tape has higher adhesive strength and Young's Modulus value than gum seems unsupported by our experiment. As previously stated, within our experiment the high velocity of the steel sphere is able to push away the very thin adhesive layer of the tape and interact mostly with the non-adhesive film beneath it. This interaction caused inelastic collisions unanticipated by the previous studies, which tested for Young's Modulus and adhesive strength in highly controlled and perfected environments where the adhesive had an appropriate amount of time to bond (9,10,13,15). Our experiment was able to test the two adhesives in a way that the gum seemed more able to mitigate energy loss in most instances as it accounted for unanticipated conditions that come with high velocity and limited bonding time for the connection points.

We are confident in reporting that when certain adhesives are added to a system that depends highly on elasticity, the adhesives are able to significantly remove energy from that system. There are also instances when the application of a certain adhesive tends to cause an increase in chaotic interactions due to the heterogeneity of collision types. Heterogeneity causes further removal of energy from the system rather than simplifying it as we hypothesized. This unanticipated energy loss implies that complex systems cannot simply be optimized via the introduction of intermediaries such as adhesives that conceptually may serve to lessen external factors. In practice, adhesive substances involved in collisions are much more complex than expected. Our results suggest that when an experimental procedure is being set up that requires the removal of confounding variables and radical interactions inherent in near-elastic collisions, these variables cannot simply be removed by the presence of adhesives. We suggest that our study can be generalized to systems that utilize highly elastic collisions to perpetuate motion with many intermediary bodies of the same type of material between them. Specifically, our results are likely applicable to other adhesives that are film-bound and putty-like of far lesser elastic modulus than the system and of home-accessible adhesive strength.

In conclusion, although this study did not fully account for all properties of the adhesives that caused such differing values, we have proposed appropriate theories asserting possible rationality for these occurrences. Overall, this experiment suggests that adhesives in an elastic system serve to largely remove energy from that system due to their inelasticity. Our results also suggests that adhesives may create a more chaotic system by forming heterogeneous bodies of motion rather than more simplified ones through coupling. These results are vital for determining ways in which energy can be maintained within a system dealing with elastic collisions allows for more efficient procedures to be modeled and engineering practices to be adopted.

MATERIALS AND METHODS

Throughout the experiment, the temperature was kept at room level (about 20 °C), and the same Newton's Cradle was utilized for all trials. The pendulum (height: 18.0 cm,

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width: 17.5 cm, depth: 14.7 cm) weighed approximately 370 grams. For each trial, a camera with the capacity to record at a minimum of 30 frames per second was placed level with the spheres of the Newton's Cradle approximately two feet away. A triangular-prism-shaped ruler was placed directly in front of the spheres so that it could not interfere with the movement of the spheres themselves yet was still able to accurately measure their horizontal distance reached. The center of the ruler (15.0 cm mark) was placed at the center of the middle sphere. Each time a trial was performed the center spheres were pulled directly above the 27 cm mark. With a vertical string/sphere length of 13.4 cm and a central horizontal resting place of approximately 19.0 cm on the ruler, the resulting angle at which the sphere was released was calculated via simple trigonometry to be around 31 degrees for each trial. Each treatment was recorded in full for 10 trials; each trial was allowed to proceed for at least five swings of the final sphere. The footage was then scrubbed to find the farthest point the last sphere reached for the first five swings of every trial. This distance was recorded for all treatments and then subtracted from the resting place of the farthest-reaching point of the final sphere which was most commonly found to be around 10.5 cm, but due to minute shifts in the ruler between each recording was recalculated each time for accuracy. The mean value and standard error were found and compiled to the nearest millimeter (**Table 1**). The mean and standard error of differences in the distance lost were compiled (**Table 2**) and visualized (**Figure 2**).

The adhesives were applied in different ways. The gum was a half stick of EXTRA brand gum that was run under lukewarm water for approximately 20 seconds. The gum was applied to the front of each affected sphere and was switched out for each increase in layer to avoid a difference in adhesiveness between each trial. The tape (Duck Tape brand duct tape) was cut into rectangles measuring approximately 5 x 4 cm and was folded back in on itself so that both sides were adhesive. Like the gum, the tape was replaced between each treatment and was applied to the face of each of the affected spheres. Between each treatment, the spheres were thoroughly washed with water and hard scrubbed to eliminate all old residue that may have affected the accuracy of the trial. The spheres were also fully washed between each use of a differing adhesive type.

For the calculations made to find the average distance reached, all numbers were taken from a sample of ten trials, and each margin of error listed was computed as standard error (standard deviation divided by the square root of the number of trials) times the value of 2.262 (critical value to achieve 95% confidence at 9 degrees freedom) (16).

The data were found by reviewing footage on a frame-by-frame basis and subtracting the original resting point of the final sphere from the farthest point it reached. All values were rounded to the nearest millimeter. To calculate the average decrease in distance, the values were calculated by subtracting the average distance reached by the first swing from the second, the second from the third, the third from the fourth, and the fourth from the fifth. The average was found from this sample of four differences, and the margin of error was drawn from the standard error multiplied by 3.182 for 95% confidence (16).

The energy equations were determined by the utilization of the equation $\mathbf{0.5V^2M = J}$, where the mass of the untampered sphere was calculated to be 0.0319 kg, the taped sphere was 0.0324 kg, and the gum-attached sphere was 0.0332 kg (17). Velocity was calculated via the equation $\mathbf{\sqrt{2GL[1-\cos\theta]} = V}$, where gravity was simplified to 9.8 m/s², and the length was the previously stated value of 0.134 m (7). Initial values of energy were calculated by utilizing the mass of a single sphere under the associated treatment, and the previously mentioned angle of 31°. For final energy calculations, the mass of all five spheres was utilized due to all treatments causing the five spheres to move together by the end of the five swings, except for the control, where the spheres were still significantly separated. The appropriate massing was utilized for every affected sphere for each treatment. The degrees were determined by the usage of simple trigonometry and the determined average displacement. The listed error bars are determined by taking the SE times 2.262 for 95% confidence. The significance tests used to determine *p*-values were t-tests with alpha values of 0.05.

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