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Honors Physics Period 7

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Honors Physics Rube Goldberg Machine Lab Report

Official Video Link: https://www.youtube.com/watch?v=LdfQvVIDHmM

Introduction

Energy and Work are something that occurs all around us, even though it isn't visible to the eye, understanding these concepts allows us to explore potential and kinetic energy. Energy and Work sound completely different, but they are connected: energy is the ability to do work, and work is the transfer of energy when a force moves an object. Energy comes in a few different forms that should sound familiar: potential energy (the potential to do work) and kinetic energy (energy used for motion). Although we cannot see the physical embodiment of energy and work, there are still ways to quantify energy through a system. One way this can be done is through the demonstration of Rube Goldberg machines, and in this Lab, we will explore energy and work through a Rube Goldberg machine that I built.

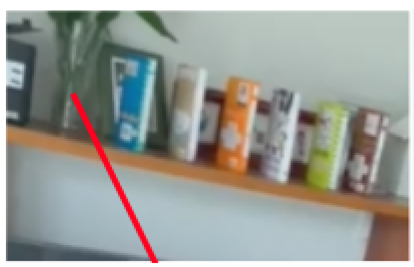
Scientific Principles

One scientific principle that is important to energy is the Conservation of Energy which states that total energy is constant throughout any process, and that energy can be changed from one form to another. This is an important concept because there will be many different energy transformations in the Rube Goldberg machine, and there will be many kinds of energy that are being shown in the whole process. The conservation of energy will be able to show how all energy is related to each other and can set up a fundamental understanding of how potential energy is able to be transferred into kinetic energy.

Another scientific concept is the Work-Energy Theorem, which states that the net work done on an object is equal to the change in the object's kinetic energy. With this, we can derive the equation of $f*d*\cos(x)=(½)*m*v$. But most importantly, this theorem focuses on what the output of net work is, which could be any real number ranging from negative to positive. When the net force is zero, we know that there is no change in the kinetic energy; however, when the net force is positive, kinetic energy increases in the direction of the object's motion, and when the net force is negative, kinetic energy increases in the opposite direction of the object's motion, hence slowing it down.

Overview of Design

The Rube Goldberg machine started off with books that stood up vertically, and they were supposed to act like dominos, and with a push, they would topple over. At the end of the sequence of books, the final book would fall flat onto a stretched dental floss that is tied to a vase which is also tied to a tissue box at the other end. Because dental floss is not visible within the picture, there is a red line that relatively shows where it is.



The string would move and pull the tissue box, which would hit a roll of tape at the edge of the table, and the roll of tape would roll off the table to a very small chair by a self-made track from cardboard and would hit a tennis ball at the edge of the chair. The tennis ball would fall and it would go down another cardboard track and would roll against a curved cardboard wall that would redirect it to a bunch of dominos.

The dominos would keep falling, and at the very end of the line, the dominos would pass their energy onto the books, and the final book would have a dental floss connected to a cardboard stopper for a marble right above, which would pull the cardboard stopper away from the marble and allow gravity to act on the marble and let it roll down to a paper tube.

On the other side of the paper tube, there is a row of books, and the marble would have enough kinetic energy to knock the first book down and consequently start another domino effect. The very last book again has dental floss tied to it, but this time, it is connected to a ladle stuck on the wall with blue tack and a spring hooked onto it.

When the last book falls, the dental floss would pull the ladle down and the spring would keep it from falling to the floor, and that free-falling kinetic energy would pull the spring hard enough to turn on the lights.

Types of Energy

Kinetic Energy appears in every scenario in this Rube Goldberg machine. It is present when the domino effect happens with the books and also actual dominos because these objects are moving and they are doing work within that moment. Another example would be when the roll of tape and tennis ball was pushed onto a negatively inclined track, it also expressed velocity during both of those times. Things that were falling also had kinetic energy, this applies to the ladle which fell when it was tugged by the dental floss. All of these are related to one common factor: velocity.

Gravitational potential energy applies to every object, even the ones on the floor. This included the books, the roll of tape, the tennis ball, the dominoes, the marble, and the ladle. It is quite self-explanatory for almost everything except for the books and the dominoes on the ground level, and it is due to the fact that they are above the zero reference level. One unique thing about the dominoes and books is that when they are standing upright, their center of mass becomes the altitude. Therefore, even when they are on ground level, they still exert some sort of gravitational potential energy when they are standing upright. Finally, another form of potential energy is the potential spring energy, where its only presence is in the last scene, where the ladle is dropped and stretches the spring.

Transformation 1 (Book to Book)

Simulation for Transformation 1 video: https://youtu.be/JCekR3OhSAA

The book-to-book transformation included two types of energy, gravitational potential energy, and also the kinetic energy. This book-to-book transformation only applies to the first part of the Rube Goldberg machine, the calculations include the mass of the specific Diary of a Wimpy Kid books. Since within this scenario, everything is on the shelf, the shelf can be the zero reference point.

The first part is having an overview of the initial and final energy. Which is the kinetic energy from the previous book and the gravitational potential energy of the current book, and the final energy would be the kinetic energy of the current book.

In the system, we can identify the Earth, because it is the main factor for gravitational potential energy. The previous book also matters because it brings in kinetic energy. The current book would also be part of the system because the initial energy flow occurs from its gravitational potential energy and the final energy flow is the kinetic energy that is being converted into.

For the calculation of gravitational potential energy, we only need the mass of the book in kilograms and also the height of the book in meters. For the height of the book when it is standing upright, we need to divide it by two because that is where the center of mass is. By using a scale, I was able to find that the mass of the book is 0.307 kilograms and the height of the center of mass is 0.1016 meters. Because the constant for gravity is 9.8 m/s^2, we have all the requirements needed for the calculation of gravitational potential energy. The equation is m*g*h = (0.307kg)(9.8m/s^2)(0.1016m) = 0.305674 Joules.

Now we also need to calculate the kinetic energy of when the current book falls. Since the kinetic energy equation requires mass (which has already been identified) and velocity, velocity is the only factor that we need to find. We can use this by doing a video analysis through Logger Pro and allow it to quantify the velocity of the book whilst it is falling. Logger Pro gave two different types of velocity, the velocity for the horizontal direction and the velocity for the vertical direction. To calculate the overall velocity, we need to use Pythagorean's theorem to be able to quantify the velocity.

X Velocity	Y Velocity	Velocity
-69.66305181	-24.04688208	73.69663035
-77.06197248	-38.34058793	86.07292423
-83.35040826	-56.28429057	100.5744099
-87.46855371	-78.60335037	117.597766
-76.98609698	-88.63948886	117.4045064
-59.8048107	-85.83071436	104.6113135

These values that are given are all under the units of inches per second.

In order to give a single value for velocity which is needed in the kinetic energy equation. Averaging all different increments of velocity can satisfy and represent all the velocities into one single number: 99.9929 inches per second, which is the velocity, the inches must be converted into meters for it to be usable in any physics equation. We can divide the speed value by 39.37 to get the velocity in terms of meters per second, but I used a google calculator to provide that value.

99.99292506	=	2.539820296524
Inch / Second		Meter per second

We can plug in the values that we got into the kinetic equation, ½(0.307kg)(2.5398m/s)^2 = which gives us 0.9901 Joules of energy. Keep in mind that the kinetic energy for the current book not only includes the gravitational potential energy, but it also includes the kinetic energy from the previous that falls on it to pass on the domino effect.

Under a system without any sort of friction calculating the kinetic energy of the previous book is extremely easy. Since we know that the kinetic energy of the current book is equal to the sum of the kinetic energy of the previous book and the potential of the current book ($KE_{PB}+Ug_{CB}=KE_{CB}$), we can use the property of equality to get this equation ($KE_{PB}=KE_{CB}-Ug_{CB}$). The kinetic energy of the previous book can be found, 0.9901J-0.305674J=0.684426J.

But it is simply impossible to simulate a frictionless Rube Goldberg machine, as that is an impossible situation. Therefore, I used another video analysis on the previous book just so I could identify how much energy is lost as thermal energy. I captured the velocity within the interval of the previous after being was hit, but before hitting the current book. By using the same methods, I was able to get the velocity of 2.0265 meters per second. Which gives the kinetic energy of 0.63037 Joules, which is less than the hypothesized kinetic energy under frictionless conditions, and we can say that 0.054056 Joules of energy was lost as thermal energy.

<u>Power Calculation:</u> The equation is work/time. For this calculation, the focus would be the work done by gravity over time. In further explanation, it means that the whole point is to know how much time it is taking for gravity to turn the book's gravitational potential energy to zero. The amount of time for my book falling was 0.1 seconds, which is shown in the image given, and the gravitational potential energy for the book is (0.307kg)(9.8m/s^2)(0.1016m)=0.305674 Joules. 0.305674/0.1= 3.05674 Watts(J/s).

Time	X Velocity	Y Velocity	Velocity
0.60	-67.46	-20.12	70.40
0.63	-68.41	-30.84	75.04
0.67	-69.07	-45.46	82.69
0.70	-69.22	-59.11	91.02

Transformation 2 (Roll of tape to the ball)

<u>Simulation for Transformation 2 video:</u> https://youtu.be/CB9R9-XL__A

For the roll of tape to the ball, the energy that is involved with these two objects are kinetic energy and potential energy. In the initial energy flow, it is expected that there is the kinetic energy of the tape and also the gravitational potential energy of the tennis ball. In the final energy flow, there will only be kinetic energy. For transformations 1 to 3, this pattern would be apparent time and time again.

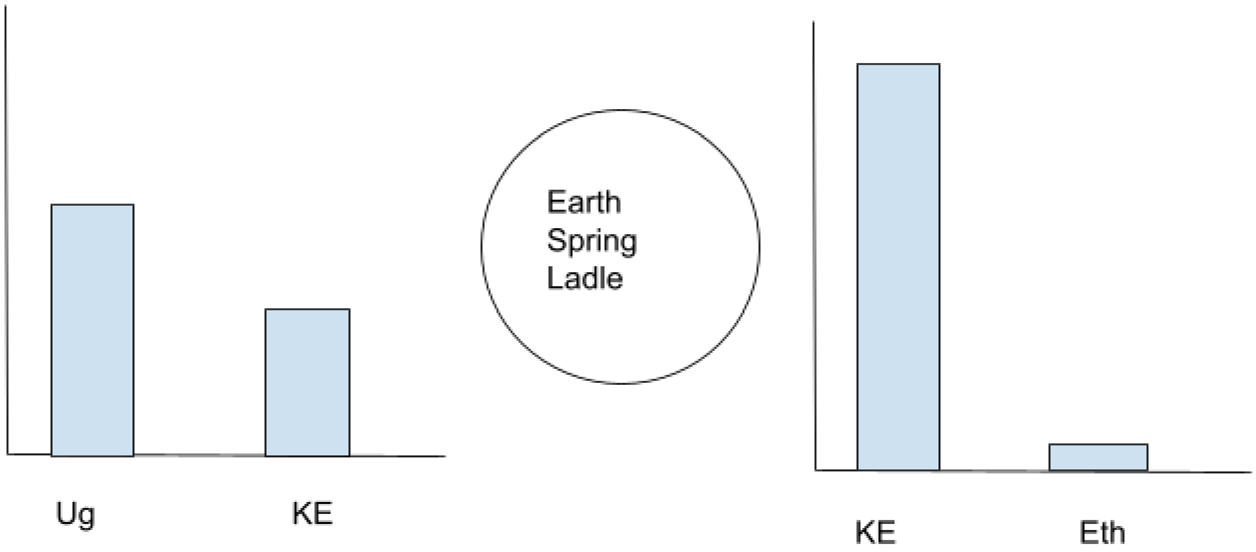
First of all, using video analysis, I was able to find the x and y velocity for the roll of tape. Then, by using Pythagorean's theorem, the velocity of the roll of tape can be calculated, which is 82.879cm/s. Converting it into m/s, it would be 0.82879m/s. The mass for the roll of tape is 16 grams, which is 0.016kg. When we plug it into the kinetic energy equation, $(\frac{1}{2})(0.016kg)(0.82879)^2=0.00663J$.

The gravitational potential energy for the tennis ball is also part of the initial energy flow. However, unlike kinetic energy, Ug is much easier to calculate. All that is needed is the height, and multiply the mass, height, and the gravity constant, Ug can be found. The height of the chair the ball is on is 24 cm, but the ball itself is 7 cm. Nevertheless, the center of mass for the ball is 3.5cm. This means that the height overall would be 27.5cm, also 0.275 meters. Therefore, $(0.016kg)(9.8m/s^2)(0.275m)$, the ball has the potential energy of 0.04312J.

Now to calculate the final energy flow, the kinetic energy for the tennis ball is needed. Using Logger Pro, allows the velocity of the tennis ball to be identified. The velocity of the tennis ball is 0.893929m/s. The mass of the tennis ball is 58 grams, so the kinetic energy equation: $(\frac{1}{2})(0.058kg)(0.893929m/s)^2=0.023174J$.

It is obvious that the final energy flow is lower than the initial one, considering that the initial energy flow is 0.04975J (0.00663J+0.04312J), and the final energy flow is 0.023174J. To find the energy that is lost as thermal energy, we need to subtract the final from the initial energy flow, which gives the value of 0.026575J of energy lost.

This makes sense because when the roll of tape hits the tennis ball, the tennis ball does not directly fall off the chair. There is still some distance that the ball needs to cover before reaching the edge and falling off, this means that most of the energy lost is when the tennis ball was rolling toward the edge due to friction.



Ug=Us+Eth

Transformation 3 (ball to dominoes)

Simulation for Transformation 3: https://youtu.be/diXtkKkI1r4

This transformation is also similar to the other two in the previous examples, and this time, it would be the transformation of a tennis ball to a notebook standing upright. The initial energy flow would include the gravitational potential energy of the book standing upright and also the kinetic energy of the tennis ball. Both forms of these energy transformations would change to the kinetic energy of the notebook falling.

To calculate the kinetic energy of the tennis ball, we require the mass and velocity of the tennis ball. By now, this process should be pretty self-explanatory and straightforward, as a video analysis would be done by Logger Pro, which shows that the velocity of the tennis ball is 59.558cm/s, correspondingly 0.59558m/s. Also, the y-velocity is not included, and the Pythagorean theorem is not needed because the y-position of the tennis ball does not change since it is rolling on flat ground. The mass of the tennis ball is 0.058 kg. The kinetic energy of the tennis ball is

(½)(0.058kg)(0.59558m/s)^2=0.01028J

The gravitational potential energy of the notebook standing upright is 7.5cm tall. Originally, the height of the book itself is 15cm, but for the center of mass, the height must be halved. But height is in the units of meters, therefore, 0.075 meters would be used instead for the calculations. The mass of the notebook is 122 grams, 0.122kg. This gives us a gravitational potential energy of (0.122kg)(9.8m/s^2)(0.075m)=0.08967J.

Finally, for the final energy flow, the kinetic energy of only the notebook falling is included as a transformation. The velocity can be calculated by using another video analysis and it is 0.2764m/s. The mass of the notebook was also measured in the previous paragraph, which is 0.122kg. The kinetic energy of the notebook falling would be (½)(0.122kg)(0.2764m/s)^2=0.00466J.

The energy lost as thermal energy due to friction and air resistance is (0.08967+0.01028)-0.00466=0.09529J. This could be due to the ball rolling on the floor and losing most of its kinetic energy from friction and air resistance

Transformation 4 (Work of Ladle in Ug to Us)

This transformation is quite special compared to the other transformations that have been listed, and it is because it involves elastic potential energy. So overall, we would expect to see elastic potential energy and gravitational potential energy only.

First, it is important to show what energy is being converted from one to another. We know that the final energy flow must be elastic potential energy, and also some thermal energy is lost. In our initial energy flow, we know that there is going to be kinetic energy. In the overview, it basically means that our gravitational potential energy will be transformed into elastic potential energy. We can quantify that as Ug=Us.

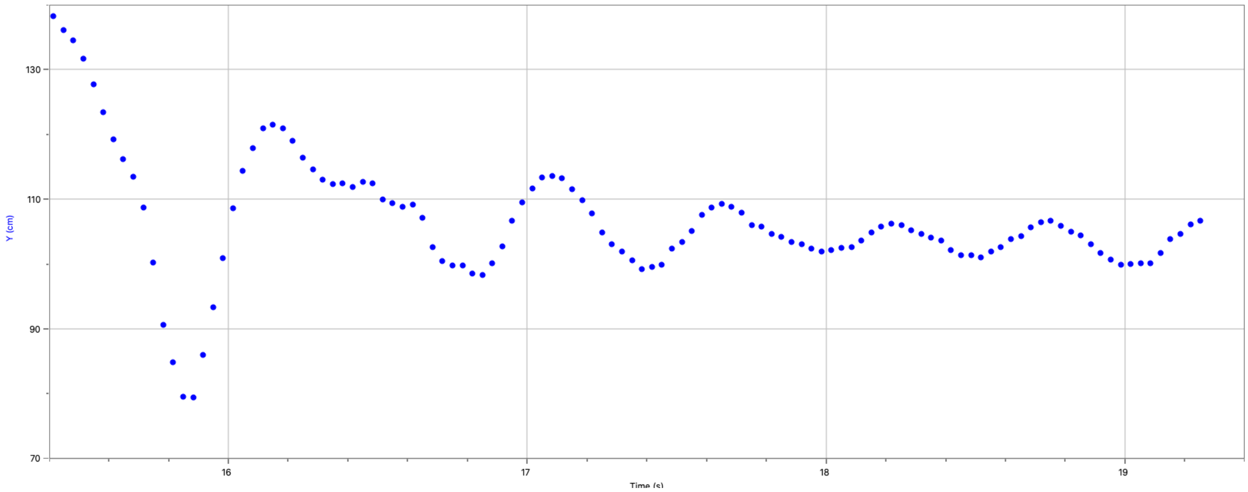
To calculate Ug, is very simple because we already know all of the components that are needed for the calculation. For the mass, we know that mass of the ladle is 0.154kg, and we also know that the height is 135 cm, which is 1.35 m. Therefore, our Ug is 2.03742J.

The difficult part is to calculate the elastic potential energy because we need to know the spring constant. However, the spring that I used in my Rube Goldberg machine was unable to be found, therefore improvisation was needed. So first we need to find the natural position of the spring, so I recorded the y-velocity of my spring when it was falling. First of all, when the ladle was falling, it would keep increasing in the y-velocity, however, once it passes a certain point, the velocity will begin to decrease. All we need to do is find the increase in y-velocity between each point that has been plotted and observe when the velocity is at its peak in the negative direction (since we know the ladle is falling downwards). Since once the spring passes its natural position, it will begin to pull the weight back up, thus decreasing the y-velocity in the negative direction.

Time	Y	Y-velocity	y-velocity increase per second	
15.415	138.227	-61.929		
15.449	136.049	-62.515	-0.586	
15.482	134.530	-73.517	-11.001	
15.516	131.722	-98.591	-25.075	
15.549	127.690	-116.920	-18.329	
15.582	123.433	-119.927	-3.007	
15.616	119.212	-109.167	10.761	
15.649	116.162	-102.670	6.496	
15.682	113.453	-130.224	-27.554	
15.716	108.739	-191.137	-60.913	natural position
15.749	100.276	-237.748	-46.612	
15.782	90.620	-216.992	20.757	
15.816	84.839	-154.299	62.693	
15.849	79.496	-57.740	96.559	
15.883	79.463	78.118	135.858	

Now we need to find the y-position for that specific time frame, and it is 108.042 cm in height

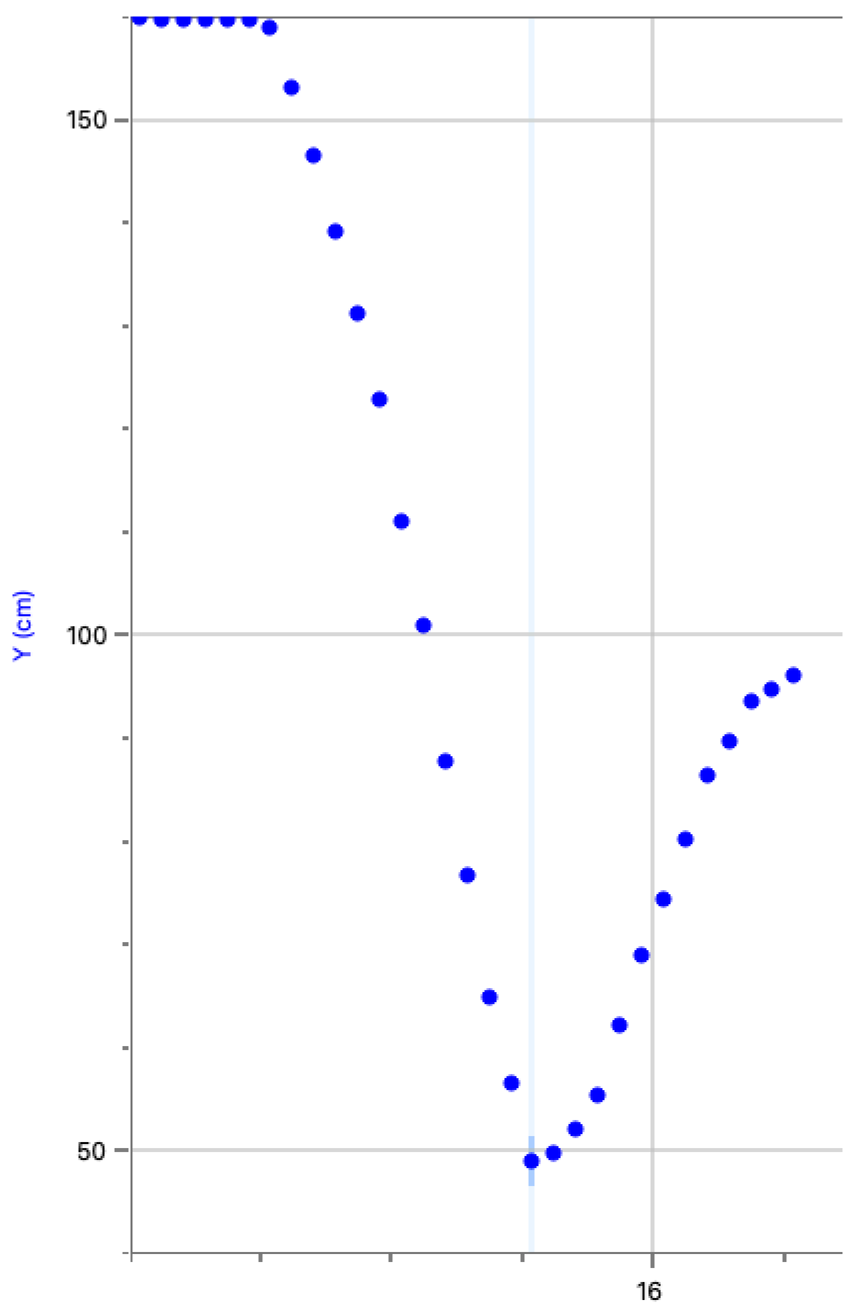
To calculate the spring constant, Hooke's Law is needed. I was able to find the spring constant through video analysis. So one factor that is a given is the weight of the ladle, which is 1.5092N. Now Hooke's Law states that F=-k*x, so we have the F component, now we only need the x, which is the stretch of the spring (stretched position - natural position). But the force would only matter if it is hanging on the mass and staying still. For that, to find what y-position the spring would be when the ladle is not moving, I decided to use some plotting from the video analysis.



This is a graph for the y position of the spring, and notice throughout the end of the video, the ladle is bouncing up and down. Another thing is that it is converging to a single point, and it can be expected that when the ladle stops moving, it would be a flat line on that y-position. What was done here, was to take every point that is creating an oscillation, and average it to find the y-position of when only the ladle is hanging onto the spring without any external forces, that position is 104.363 cm.

Now all that is the stretch of the spring is 108.042-104.363=3.679cm. Therefore, with Hooke's law, we can identify this as 1.5092=k*(0.03679m). The Spring constant is 41.02201N/m.

Now with the spring constant, we can find the elastic potential energy. This begins by finding the maximum stretch of the spring, and since we already know when the resting position of the spring is, we just need to find the y-position of the spring when it is at the lowest y- position.



150
100
50
Y (cm)
16

Time	X	Y	Y-velocity	y-velocity increase per second	
15.415	294.539	138.227	-61.929		
15.449	300.382	136.049	-62.515	-0.586	
15.482	306.500	134.530	-73.517	-11.001	
15.516	308.446	131.722	-98.591	-25.075	
15.549	308.299	127.690	-116.920	-18.329	
15.582	306.086	123.433	-119.927	-3.007	
15.616	301.988	119.212	-109.167	10.761	
15.649	295.695	116.162	-102.670	6.496	
15.682	287.746	113.453	-130.224	-27.554	
15.716	278.424	108.739	-191.137	-60.913	natural position
15.749	271.433	100.276	-237.748	-46.612	
15.782	266.340	90.620	-216.992	20.757	
15.816	269.156	84.839	-154.299	62.693	
15.849	273.598	79.496	-57.740	96.559	
15.883	274.540	79.463	78.118	135.858	Lowest position
15.916	273.703	85.949	177.152	99.034	
15.949	274.674	93.319	214.114	36.962	
15.983	275.536	100.940	217.419	3.305	
16.016	278.594	108.595	191.099	-26.320	
16.049	280.507	114.375	142.880	-48.219	
16.083	284.733	117.868	98.022	-44.858	
16.116	287.549	120.931	52.375	-45.646	

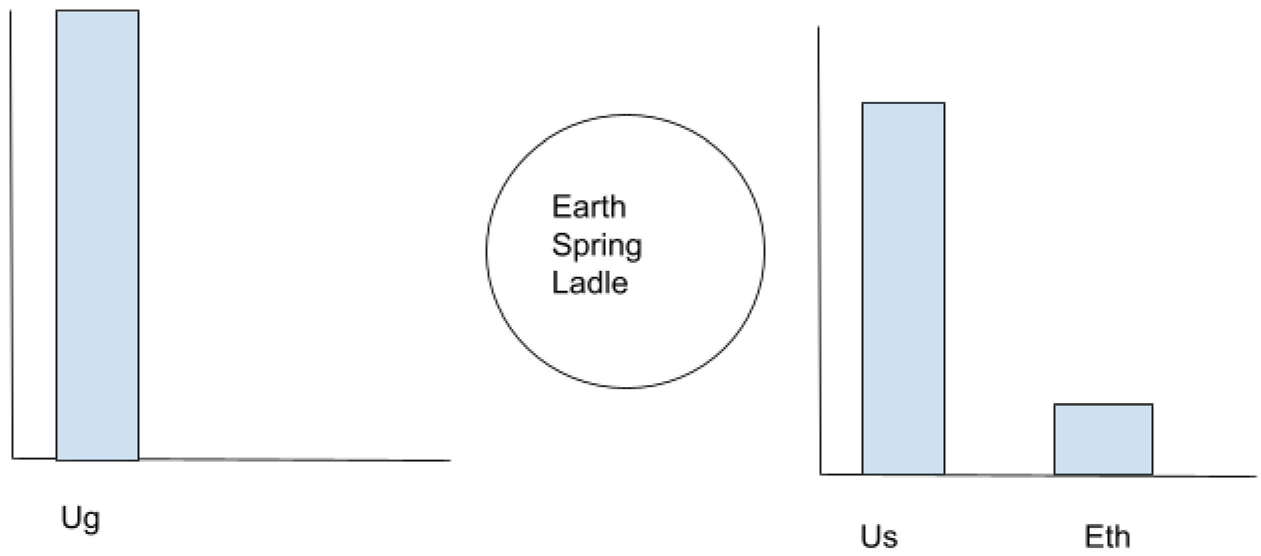
Using the distance formula, we can use the y and x positions to find the overall stretch of the string, which should be the hypotenuse (we need to use the x-position because it is also moving left and right). The stretch of the spring from the natural position of the spring to the absolute most it can stretch is 29.533 centimeters, also known as the change in position.

So if we put all the components in the elastic potential energy equation,

$U_s=(½)(41.02201 N/m)(0.29533 m)^2=1.7889 J$

Therefore, our gravitational potential energy transformed into elastic potential energy. From 2.03742J to 1.7889J, and lost 0.24852J of energy as thermal energy

<u>LOL Diagram:</u>



Ug=Us+Eth

Energy Loss

For Transformation 1, the energy loss was 0.054056J, considering the size of the objects that were being dealt with (full-sized books). An energy loss of 0.05J was quite efficient, and dominoes are quite energy efficient. This could be widely due to the fact that the intervals from one book hitting the other were so small that air resistance could not create a significant impact before the next book was knocked over.

Transformation 2 has the lowest energy loss out of all the scenarios in this Rube Goldberg machine, with an energy loss of 0.026575J. This is likely because the scenario was dealing with round objects, which are more aerodynamic compared to other objects such as books. Therefore, the energy loss due to air resistance was significantly lower than others, hence the low energy loss.

The energy loss in Transformation 3 was significantly high when the size of the system is not even large at all, losing 0.09529J. This was because the impact of the tennis ball hitting the notebook was not large that it only tipped over the book a little bit, and allow gravity to do the rest of the work, this causes low velocity and would impact the kinetic energy calculations for the notebook itself. The notebook was also opened up a little bit to balance it better, so some kinetic energy from the tennis ball might not move the notebook, but only close the gap between the pages.

Finally, Transformation 4 has the greatest energy loss out of all the transformations, with an energy loss of 0.24852J. However, all energy that appears in the system is very high. The energy loss can be greatly contributed to the spring's material since it was made from plastic, the material may have deformed because I have tested the Rube Golberg machine, and might have caused it to wear out.

Efficiency is important when talking about energy loss because it shows what the output is given the amount of energy inputted. We know that the original energy input can be calculated by the gravitational potential energy of the first book, and the energy outputted is the final energy flow from Transformation 4.

The efficiency equation is (output/input)*100. To find the input of the entire system, I calculated the gravitational potential energy of the first book: height=0.105m, weight= 0.407kg. The input of the system would be (1.5909m)(9.8m/s^2)(0.307kg)^2=4.7863J. The output of the system would be 1.7889J, the elastic potential energy of the longest stretch for the string, plus the gravitational potential energy of the ladle when it is at the bottom; where the height is 79.463 cm tall, and the ladle is 0.154kg, therefore 1.7889J+((0.79463m)(9.8m/s^2)(0.154kg))=2.9881J, which is the final calculation for output.

(2.9881J/4.7863J)*100=62.43% efficiency

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15.482	306.500	134.530	-73.517	-11.001	
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15.816	269.156	84.839	-154.299	62.693	
15.849	273.598	79.496	-57.740	96.559	
15.883	274.540	79.463	78.118	135.858	Lowest position
15.916	273.703	85.949	177.152	99.034	
15.949	274.674	93.319	214.114	36.962	
15.983	275.536	100.940	217.419	3.305	
16.016	278.594	108.595	191.099	-26.320	

Why I Used the Resources I Used

For most of the components within my Rube Goldberg machine, I tried to use objects that I already owned instead of buying completely new ones. This plays into the sustainability part of the project. However, I still did use objects such as paper, cardboard, and tape during the process. Creating some sort of waste during the process of building the Rube Golberg machine was inevitable, yet I asked my dad to bring home cardboard boxes that he was about to throw away.

At the beginning of the project, I encountered the big challenge of having very limited resources. I had to go to my dad's office to bring back things that had been stored away in his office. This included the dominoes, the tennis balls, and even the HKIS yearbooks.

What could have been done better

I could have made sure that next time, I made more tracks to make the objects in the machine move the way I wanted. One of the problems was that there was too much chance involved in trying to get the perfect try. I also used more springs in the beginning of the project instead of just one, however, springs were very unpredictable and the theoretical outcome was much different than my actual outcome. I had to get rid of lots of springs which drastically changed most of my machine. But through the experience of this project, if I ever have another chance of doing this project again, I would add more springs. Before this Rube Goldberg machine, I also did a handmade one that stuck on the wall, regardless, it was a failure because I ran out of space, and did not reach the required time of 7 seconds.