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NOTE: The following Internal Assessment was submitted as a part of my International Baccalaureate Higher Level Physics class. I received a 6 out of 7 in the class.

Spider-Man's Optimal Swinging Release Point in a Pendulum

Introduction

On June 30th, 2004, one of the best superhero movies ever was released. While I was far too young at the time to watch it in theaters, the reruns on various television networks sparked my interest. Spider-Man 2 was the first superhero movie I watched – before any Batman movies, any Iron Man movies, or even before the original Spider-Man movie released in 2002. I was fascinated by watching a teenager superhero, but even more interesting, his powers. The "sense" that Peter Parker had was cool, but the best thing for me was always his swinging motions.

Spider-Man is known as a "web-slinger", using webs shooting from his wrists to swing between buildings. In the movies and comics, it appears as though he always has just enough velocity swinging through the air. While the actors are using rigs to simulate the motion of swinging[1], I was curious as to what would happen if the trajectory was performed. The motion is like a pendulum, so I decided to find what the optimal release point of a pendulum would be in terms of maximizing distance when releasing from the web. This way, Spider-Man uses the fewest webs and can conserve energy to accomplish his mission by swinging more efficiently.

This exploration will delve into the optimal release point of a pendulum by analyzing a variety of lengths and launch angles for an object.

Theory of Pendulums

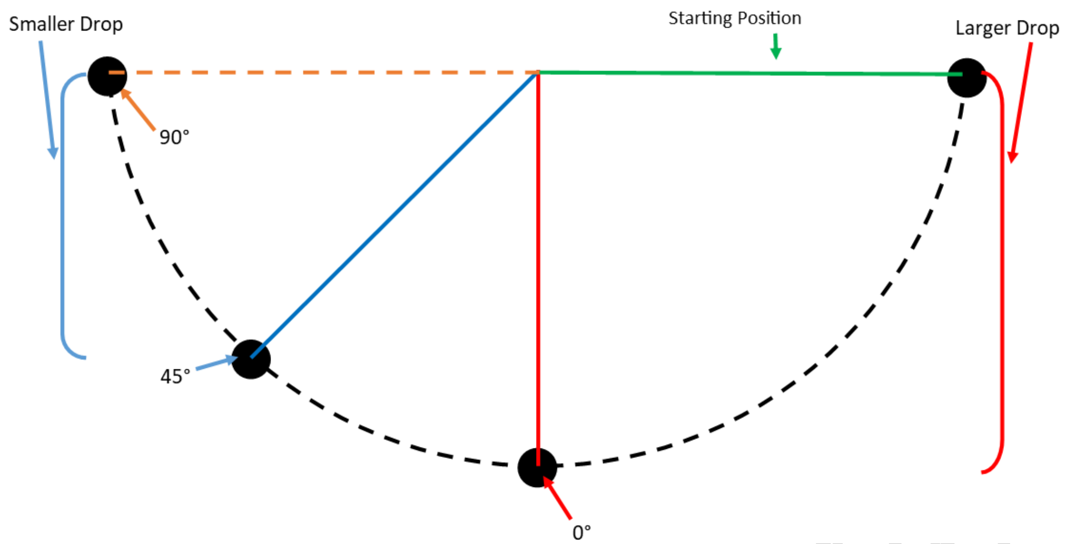
A pendulum is the system where something swings back and forth connected to a fixed location due to gravity. It goes back and forth, such as the rod under grandfather clocks or even a bowling ball being thrown.[2]

The period, or time is takes to swing one full motion or cycle, is solely dependent on the length of the pendulum. Adjusting the angle of release for a pendulum does not affect the period. This is because when a higher angle of release is used, the pendulum just swings faster to maintain the same period.

I confirmed this firsthand during a previous experiment. By manually adjusting the length, mass at the end of the pendulum, and angle of release on a pendulum while using a stopwatch to time the period for 10 full cycles, only the length adjusted the period of the pendulum. This is an important conclusion, as it means the mass does not matter and that the pendulum speeds up when it is pulled further back.

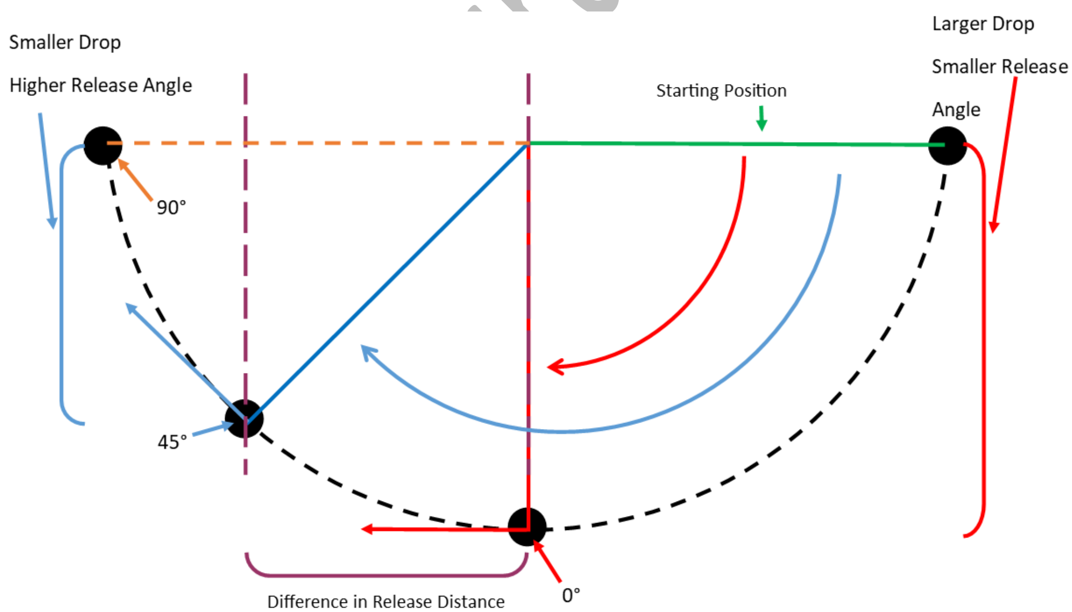
Physics equations can be used to determine just how fast the object goes along the pendulum by using conservation of energy equations. Using that gravitational potential energy is $GPE = mgh$, where m is mass, g, is gravity, and h is height and that kinetic energy is $KE = \frac{1}{2}mv^2$, where m is mass and v is velocity, a longer length of string creates more difference as the gravitational potential energy is converted to kinetic energy at the bottom of the swing. The amount that the object drops, then, is what determines the velocity of the object. Smaller drops mean the object moves less slowly while larger drops mean the opposite, as shown in the diagram below:

[1] See McCarthy – "The Physics of How The Amazing Spider-Man Swings."
[2] See Scientific American – "Swinging with a Pendulum"; examples and comprehension of concepts were gained from this source.



Therefore, a longer string creates more speed. However, the longer string also drops the object closer to the ground, giving it less time in the air before it lands. Additionally, when there is more distance between the release point and the starting point, there is a greater change in height which leads to an increased amount of velocity when the object has been released. This rules out anything before the red release point of the swing as shown below, as that would lead to the object going downward when being released.

As the angle increases, the speed decreases, although the distance slightly increases with these release points, as shown in the diagram below:



The question, then, is how much this angle should be. Obviously, if it was released straight up, then there would be no horizontal movement at all. Therefore, there is a finite value that best optimizes the distance that the object will travel.

The ideal angle lies somewhere between 0 and 90 degrees, defined where 0 is the neutral angle and 90 is the angle completely opposite the starting point where the ball goes straight up (as shown on the above diagram). The experiment will analyze the data between 0 and 60 degrees, as the goal is to maximize distance and not time spent in the air, however, the theoretical data will be computed for 75 and 90 degrees just to confirm this thought. This is because for values over 60 degrees, it is highly unlikely that there is enough velocity to go further. However, this will be confirmed later through both data and mathematical examination.

Research Question

What is the optimal release point of an object swinging in a pendulum to maximize distance traveled and how does this change as the length of the pendulum is adjusted?

Experimental Design

The purpose of this investigation is to determine the ideal release point based on changing lengths of the pendulum swing to maximize distance traveled. I will be using one rock throughout the experiment, although the actual mass of the rock should not matter as the equations regarding its movement and trajectory are independent of mass.

The height of the pendulum and Spider-Man swinging need to represent what happens in the real world. According to Emporis, a skyscraper is defined as a building "whose architectural height is at least 100 meters"[3]. Peter Parker is 5 feet and 10 inches[4], or 1.778 meters, and this can be converted to his vertical reach by using data from the NBA where about 50% of players have a reach-to-height ratio of between 1.32 and 1.35 with the median at 1.335[5]. Thus, Spider Man has a vertical reach of about 2.37 meters. The tallest obstacles on the road that Peter would have to swing over are probably around the same height as 18-wheelers, which are about 13.6 feet tall[6] or 4.15 meters. Thus, since Spider-Man is swinging with his arm above his head and he has to comfortably avoid such obstacles like these trucks as well as flagpoles and bridges, it is safe to assume that Spider-Man must stay at least 30 meters off the ground. From here, that equates to about 1/3 of the distance off the ground, or 2/3 being comprised of his web at the max. Due to constraints within the lab, I will be using 1.5 meters above the ground with varying string lengths from 1 to 0.6 meters to simulate the variation in Peter's swing, as he does not want to swing too high or too low to the ground.

My hypothesis is as follows: If an object is released from the launch angle of 40 degrees past the horizontal, then the object will travel the farthest compared to other angles because while 45 degrees is in the middle of 0 and 90 degrees, the increase in height leads me to conclude that a slightly smaller angle would be best as the rock has elevation before being cut.

Experimental Variables

The independent variable that I will be changing is the launch angle for the release point on the pendulum. The length of the string being used will be changed as well, so for each angle there will be multiple trials for each of the three lengths of string to determine if there are different optimal launch angles that vary based on the string length.

The dependent variable is the distance the rock travels. This will be measured using carbon paper, so that the rock leaves an imprint on the paper such that when the paper is moved the actual impact point can be measured using metersticks precisely instead of using estimation.

The controlled variables are everything else in the experiment. This includes the type of blade being used, the rock, the exact two support stands, the two clamps, the type of string, and the ring support attached to the stand from

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[3] See EMPORIS definition of a skyscraper.
[4] See Spider-Man Wiki on height of Peter Parker.
[5] See The Hoops Geek "What Is Standing Reach – And How Do You Measure It Correctly?" for conversion factor from height to standing reach.
[6] See TruckersReport.com infographic on Interesting Facts for height of 18-wheeler trucks.

which the rock swings. These should ensure that the experiment happens under similar conditions every trial; however, natural variance in the data is expected.

Experimental Assumptions

There are two categories of assumptions that I made in this experiment: first, the differences that may be different from what I am attempting to model with Spider-Man, and second, the differences that arise from the actual experimentation restrictions when using a pendulum.

Spider-Man shoots web fluid out of his wrists, which is flexible and stretchy that is more akin to rubber than string. However, for this experiment, I will be using string. Additionally, I will be ignoring the concerns in terms of the extreme forces present within Spider-Man's body that a regular human being would not be able to withstand. As explained by the YouTube channel *The Film Theorists*, the swings would be extremely deadly in terms of rupturing internal organs[7]. Lastly, when Spider-Man is swinging between towers, he shoots his webs while in the air to change direction and keep moving. That is nearly impossible to recreate, so the experiment will assume that Spider-Man is swinging one time and will then land on the ground after the swing, mirrored by the rock swinging and then landing on the ground. That distance will then be measured and reported as the data from this experiment.

Regarding the actual experimentation itself, I started every trial holding the rock all the way back so it was horizontal and parallel with the floor. The ring support itself was parallel to the ground as it was horizontal, so I was able to line this up accurately by ensuring the string was in line with the ring. This served two purposes: first, it made setting up every trial significantly easier to standardize, and second, it made the mathematical calculations when analyzing the theoretical data easier as well. Air resistance is ignored as it is most likely negligible on an object of such a small size as well.

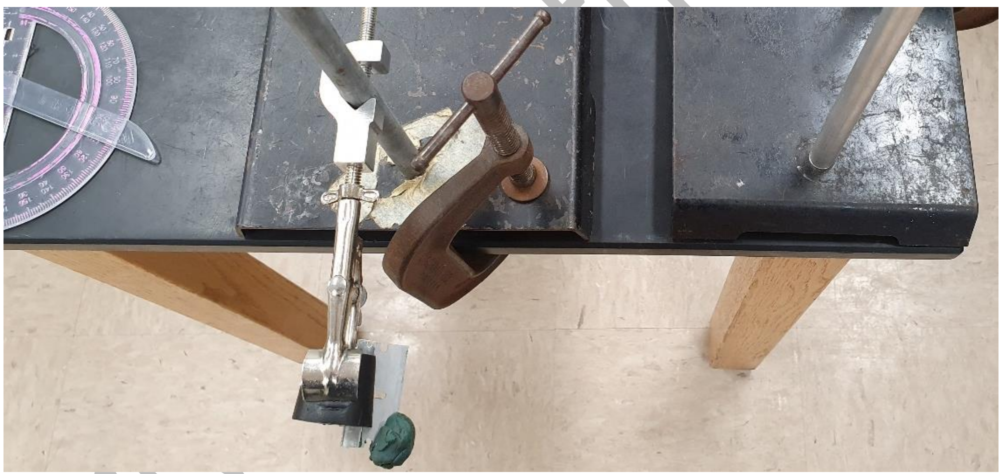
Method

1. Set up the experiment. There are a variety of things that need to be done in preparation for collecting data. First, clamp a ring stand to a table. Then, attach a ring support to the ring stand at a height of 1.504 meters above the ground. Create a cutting apparatus by taking a clamp and inserting a blade to the end. It is important to add some clay to the edge of the blade facing outwards to prevent any injuries. The picture below shows this setup.

2. Now, mass the rock.
3. Tie the thinner string to the rock and measure out a distance about 1.4 meters. The exact precision is not necessary for this measurement. Ideally, the rock has a thicker string around it (as shown in the right image above) that can then be re-used multiple times to tie string to, as this thinner string will be cut with every trial.
4. Tie this length to the ring support such that there is 1 meter between the ring support and the rock. Set up the cutting apparatus to be as close to the mass as possible, so as low as possible on this ring stand. This is very important to ensure that the string will cut accurately and efficiently.

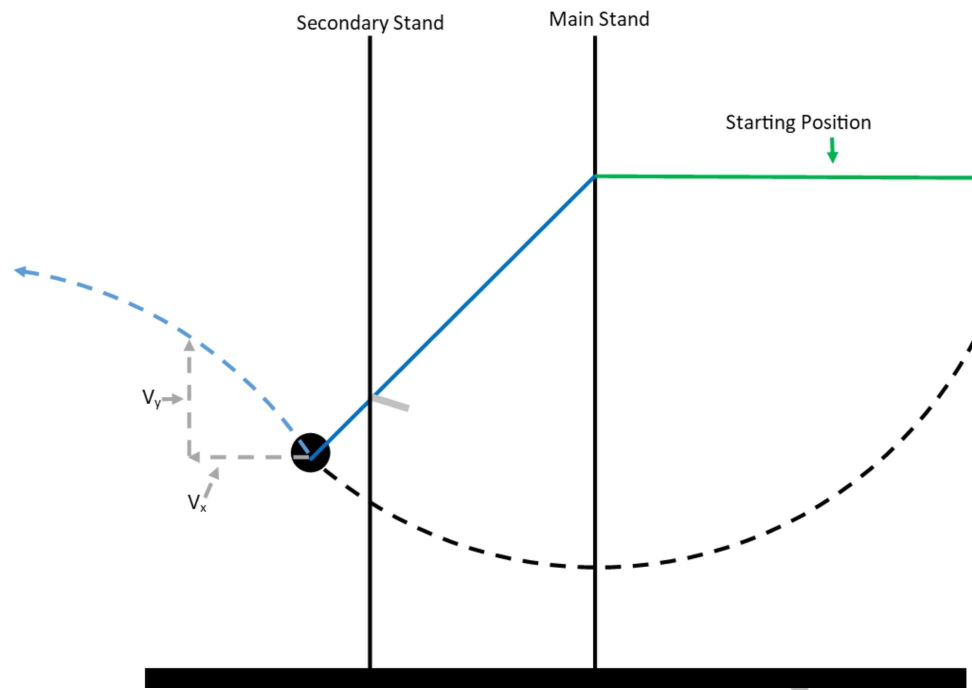
[7] See specifically 4:09 to 7:00 from Film Theory: Spiderman is DEAD! Web Swinging's Tragic Truth.

5. Set out carbon paper (as shown above). The exact location of the carbon paper can be determined in either of two possible ways. First, the theoretical values are a good indicator of where the rock will go (see Data Analysis section for these calculations). Second, doing an initial dry run of seeing how far the rock goes without taking any measurements to then place the carbon paper for a more accurate measurement three more times gives a similar result.
6. Pull the rock all the way back so that it is parallel with the ground. Release the rock, ensuring that the string remains taut upon release. The rock will swing, the string will be cut, and then the rock will go a certain distance and then hit the carbon paper which was set out using the theoretical values (calculated later in this investigation). Measure the distance that the rock has traveled[8] by removing the top layer of carbon paper and then using a ruler to go from the nearest tape mark to the mark created on the paper underneath by the rock.
7. Repeat this process (steps 3 to 6) to collect data for two more trials.
8. Now repeat the process but use lengths between the ring support and the rock of 0.8 and 0.6 meters. Tie the string to the rock, cut it a bit longer, and then attach it to the ring support for each of the three trials. After collecting this data, all the data for the launch angle of 0 degrees, or a neutral angle, has been found.
9. Take a second ring stand and keep it on the same table. Using a protractor, hold a ruler at an angle of 15 degrees from the vertical to find where the blade should be kept. Clamp the ring stand and attach the cutting apparatus so it forms a 15 degree angle with the ring support where the rock is swinging from Again, this second stand should be as far from the initial one as possible so that the blade is close to the mass, but not to the point that the distance is more than the length of string.



10. Repeat steps 3 to 8 for this new angle to find data for three lengths of string each for three trials at this angle.
11. Now adjust the second ring stand to create a launch angle of 30 degrees. At this point, depending on the exact table, it may be better to use a second table so that the second ring stand that has the cutting apparatus can be on a separate table such that the blade is cutting as close to the rock as possible.

[8] It may be useful to set up tapes along the floor of the laboratory when conducting the experiment in increments of 0.5 meters up to 3 or 4 meters. This requires more set-up time to align the ring stand with the ring support attachment point for the rock with the initial tape, but subsequent measurements can be done using the other reference tapes with only one meterstick instead of multiple ones.



12. Repeat steps 3 to 8 for this new angle to find data for three lengths of string each for three trials at this angle.
13. Repeat steps 11 and 12, adjusting the launch angle to 45 and then 60 degrees to find the distance for the three lengths of string for each of the three trials at both angles.
14. At this point, all the data for this lab has been collected. Now, analysis to comprehend and utilize the data is necessary.

Data Analysis

Height of Release: 1.504 ± 0.0005 m

Mass of Ball: 0.8464 ± 0.0001 kg

Launch Angle ±2 (degrees)	Length ±0.0005 (m)	Distance ±0.0005 (m)			Theoretical (T) (m)[9]	Average (A) (m)[10]	Difference (T – A) (m)	% Error
		Trial 1[11]	Trial 2	Trial 3				
0	1.000	1.591	1.587	1.602	1.4199	1.593	-0.174	12.2%
0	0.800	1.644	1.560	1.578	1.5009	1.594	-0.093	6.22%
0	0.600	1.528	1.573	1.542	1.4730	1.548	-0.075	5.06%
15	1.000	2.158	2.109	2.264	2.2159	2.177	0.039	1.76%
15	0.800	2.139	2.223	2.103	2.0961	2.155	-0.059	2.80%
15	0.600	2.206	1.940	2.153	1.8885	2.100	-0.211	11.2%
30	1.000	2.406	2.524	2.247	2.7400	2.392	0.348	12.7%
30	0.800	2.398	2.226	2.160	2.4304	2.261	0.169	6.96%

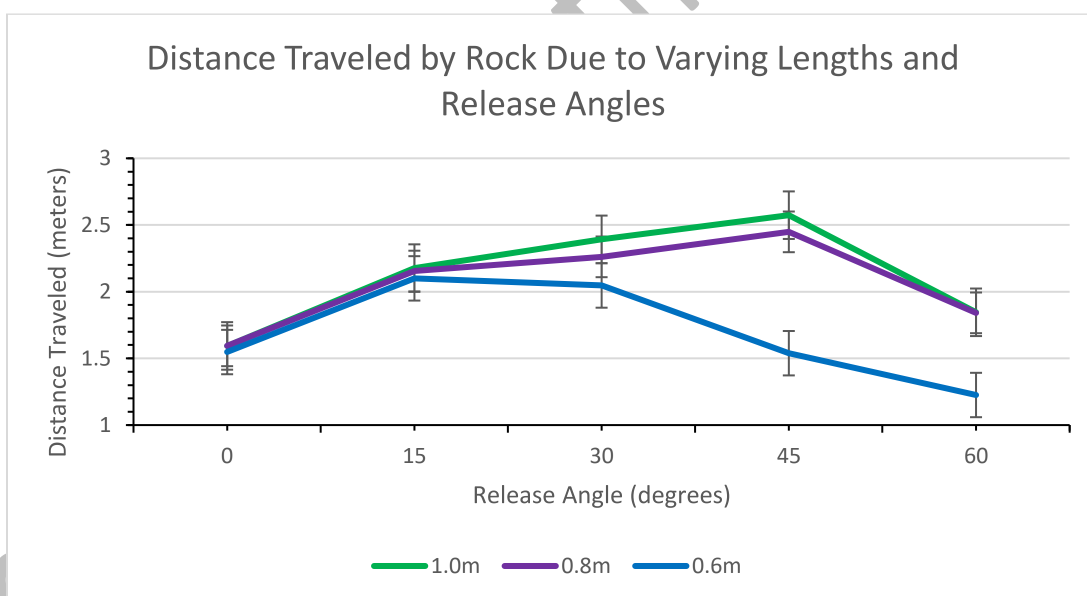
[9] A sample calculation with the formulas begins on page 8, which yields a formula for each length that can be used to find the theoretical values for any angle as well as the optimal angle.
[10] The average is reported with 3 decimal places although there were more decimal places – I used the full 4 decimal place values from each trial to calculate the averages.
[11] Each trial has 3 decimal places although the ruler could measure up to 4 decimal place; however, I removed one last digit as I felt it was too precise. I did use the value with 4 decimal places for other calculations to maintain precision of those as well.

30	0.600	1.976	2.023	2.140	2.0680	2.046	0.022	1.04%
45	1.000	2.495	2.689	2.537	2.6897	2.574	0.116	4.32%
45	0.800	2.582	2.476	2.289	2.3068	2.449	-0.142	6.15%
45	0.600	1.559	1.372	1.685	1.8955	1.539	0.357	18.8%
60	1.000	1.850	1.893	1.794	2.1294	1.846	0.284	13.3%
60	0.800	1.567	1.983	1.974	1.7886	1.842	-0.053	2.96%
60	0.600	1.354	1.226	1.098	1.4342	1.226	0.209	14.6%

Looking at the data, there does seem to be a relative amount of error that does vary among the different launch angles and length. There are a few possible reasons for this error which are discussed further in the Conclusion of this paper as possible limitations.

Overall, the greatest distance that was supposed to occur at 30 degrees compared to the other degrees that I used according to the theoretical data, but for the 1 meter and 0.8 meter lengths the greatest distance actually happened at 45 degrees although the 0.6 meter length had its longest distance at 30 degrees. However, these values also have some moderate variance to them, leading me to conclude that there might have been a slight inaccuracy during the setup such as a blade moving or being adjusted by a failed attempt a couple of degrees.

This data is graphed below, using different colors for different lengths with the launch angle on the x-axis and the distance traveled on the y-axis.



The calculations to determine the theoretical values were done using a formula that I derived from existing physics equations and theorems as well as inserting my own proof to simplify the math. The work is shown below.

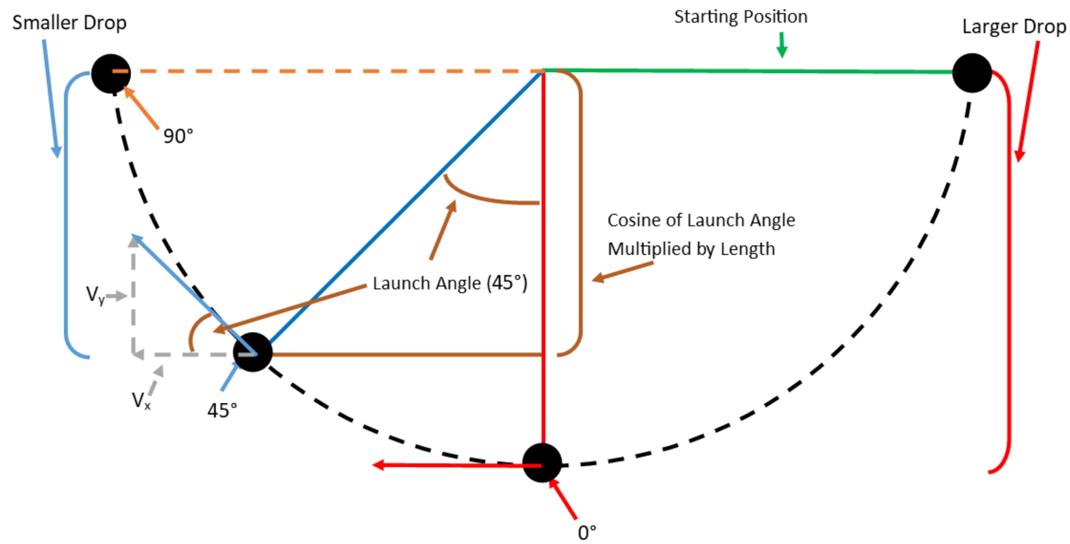
I will now demonstrate how the formula for the theoretical values was found. The velocity can be found using the following formula (where g is negative, so the length of the fall downwards is also negative):

$$PE = KE$$

$$\cancel{m}gh = \frac{1}{2}\cancel{m}v^2$$

$$v = \sqrt{2gh} = \sqrt{2g(-l)cos(\theta)}$$

The rock was being released at the neutral position, so it would have this velocity as stated in the velocity column. From other release points, the height difference from the starting point to the actual release point is not the full length of the string. Rather, it is the length multiplied the cosine of the launch angle multiplied by the string, as shown in the diagram below:



As can be seen above, finding the cosine of the launch angle yields the actual difference in height of the smaller drop, reflecting the decrease in velocity as the launch angle increases. While it is not applicable in this instance, it is instrumental in the other, larger launch angles. The following two equations are the velocity vectors in both the x and y directions where θ is the launch angle shown in brown in the above diagram. These velocity vectors represent the motion of the ball when it is cut and moving at an initial trajectory tangent to the arc.

$$V_y = V \times sin(\theta) = sin(\theta)\sqrt{2g(-l)cos(\theta)}$$

$$V_x = V \times cos(\theta) = cos(\theta)\sqrt{2g(-l)cos(\theta)}$$

The release height varies for the angles as there is an increased height for other rock release angles as shown in the initial diagrams, where h is the height above the ground at the lowest point. Multiplying by $1 - cos(\theta)$ [12] then adjusts this height based on the angle to account for variations i.e. when the angle is 15 degrees, the rock is not being released at the lowest point on the pendulum swing.

$$d_y = h + l \times (1 - cos(\theta))$$

This would factor that in by altering the release height as the distance from the rock to the ground. Now, a quadratic equation is set up using kinematic equations, although the a term is negative since acceleration acts downwards and so is d_y as it is the distance that the rock falls.

$$-d_y = \frac{1}{2}at^2 + V_y t = \frac{1}{2}gt^2 + V_y t$$

[12] This comes from the previous diagram - to find the vertical section for the release height illustrated below the brown section added to the height of the pendulum at its lowest point.

$$t = \frac{-V_y \pm \sqrt{{V_y}^2 - 2gd_y}}{g}$$

$$t = \frac{-sin(\theta)\sqrt{2g(-l)cos(\theta)} \pm \sqrt{(sin(\theta)\sqrt{2g(-l)cos(\theta)})^2 - 2g(h + l \times (1 - cos(\theta)))}}{g}$$

The above equation can be used to solve for the time that the rock spends in the air. There are two solutions, as this is a quadratic, but the negative root is thrown out as time cannot be negative. In this example, the time used is 0.32 seconds, as the a in the equation as acceleration is -9.8 m/s^2, the V_y in the equation as initial velocity in the y direction is 0, and the initial position above the ground is 0.504 m.

Now that time in the air has been found, it is multiplied by the velocity in the x direction. This example has all of it going in the horizontal direction, so it just multiplies this time by the velocity to find the distance. However, as shown in the second diagram of this paper, releasing it at an angle slightly increases the release distance. Factoring this in yields the final Total Distance result column, which is 1.42 meters in this case.

$$d_{total} = t \times V_x + lsin(\theta)$$

$$d_{total} = \frac{-sin(\theta)\sqrt{2g(-l)cos(\theta)} \pm \sqrt{(sin(\theta)\sqrt{2g(-l)cos(\theta)})^2 - 2g(h + l \times (1 - cos(\theta)))}}{g} \times cos(\theta)\sqrt{2g(-l)cos(\theta)} + lsin(\theta)$$

Now the question is to whether the positive or negative radical for the time expression should be used. The following is a proof as to why the radical is a lesser value than the term preceding it, and since time cannot be negative, the negative radical must be used in the final function.[13]

$$-\sqrt{(sin(\theta)\sqrt{2g(-l)\cos(\theta)})^2 - 2g\big(h + l \times (1 - cos(\theta))\big)} < -sin(\theta)\sqrt{2g(-l)cos(\theta)}$$

$$\cancel{2g(-l)sin^2(\theta)\cos(\theta)} - 2gh - 2gl + 2glcos(\theta) > \cancel{2g(-)lsin^2(\theta)\cos(\theta)}$$

$$h + l > lcos(\theta)$$

The above statement is true for any values of h and l when the angle θ ranges between 0 and 90 degrees, or when $cos(\theta)$ ranges from 0 to 1, as it means that any amount of height involved in the equation makes it so that the left hand side is slightly greater than l while the right hand side ranges between 0 and l. Now that this is the case, the radical must be made negative to ensure a positive time value, as shown below.

$$d_{total} = \frac{-sin(\theta)\sqrt{2g(-l)cos(\theta)} - \sqrt{(sin(\theta)\sqrt{2g(-l)cos(\theta)})^2 - 2g(h + l \times (1 - cos(\theta)))}}{g} \times cos(\theta)\sqrt{2g(-l\_cos(\theta)} + lsin(\theta)$$

From this equation, the distance for any combination of lengths and angles can be found using g as -9.8 m/s^2, θ as the angle from the vertical, l as the length of the pendulum, and h is the height off the ground at the lowest point, which in this investigation can be represented as $1.504 - l$. Thus, three equations can be formed to model each of the three different lengths:

[13] Regarding the math below this paragraph, I first squared both sides which flips the sign of the inequality as there is multiplication by negatives. Then, since g is negative, $-2g$ is positive which is what both sides are multiplied by to get the final rearrangement of $h + l > lcos(\theta)$.

$$d_{1m} = \frac{-sin(\theta)\sqrt{19.6\cos(\theta)} - \sqrt{(sin(\theta)\sqrt{19.6cos(\theta)})^2 + 19.6(0.504 + (1 - cos(\theta)))}}{-9.8} \times cos(\theta)\sqrt{19.6cos(\theta)} + sin(\theta)$$

$$\boldsymbol{d_{1m}} = \frac{sin(\theta)\sqrt{19.6\cos(\theta)} + \sqrt{19.6cos(\theta)sin^2(\theta) + 29.4784 - 19.6\cos(\theta)}}{9.8} \times cos(\theta)\sqrt{19.6cos(\theta)} + sin(\theta)$$

$$d_{0.8m} = \frac{-sin(\theta)\sqrt{15.68\cos(\theta)} - \sqrt{(sin(\theta)\sqrt{15.68cos(\theta)})^2 + 19.6(0.704 + 0.8 \times (1 - cos(\theta)))}}{-9.8} \times cos(\theta)\sqrt{15.68\cos(\theta)} + 0.8sin(\theta)$$

$$\boldsymbol{d_{0.8m}} = \frac{sin(\theta)\sqrt{15.68\cos(\theta)} + \sqrt{15.68cos(\theta)sin^2(\theta) + 29.4784 - 15.68\cos(\theta)}}{9.8} \times cos(\theta)\sqrt{15.68\cos(\theta)} + 0.8sin(\theta)$$

$$d_{0.6m} = \frac{-sin(\theta)\sqrt{11.76\cos(\theta)} - \sqrt{(sin(\theta)\sqrt{11.76cos(\theta)})^2 + 19.6(0.904 + 0.6 \times (1 - cos(\theta)))}}{-9.8} \times cos(\theta)\sqrt{11.76\cos(\theta)} + 0.6sin(\theta)$$

$$\boldsymbol{d_{0.6m}} = \frac{sin(\theta)\sqrt{11.76\cos(\theta)} + \sqrt{11.76cos(\theta)sin^2(\theta) + 29.4784 - 11.76\cos((\theta))}}{9.8} \times cos(\theta)\sqrt{11.76\cos(\theta)} + 0.6sin(\theta)$$

To find the ideal release angles, take the derivative of each distance function with respect to θ and then set it equal to 0 to find the maximum value that the rock can travel. For 1, 0.8, and 0.6 meters, the ideal angles are 36.219, 33.642, and 30.396, respectively according to this theoretical model[14]. While the experiment would be unable to go to such precision[15], using a model allows for such examination. This leads to the conclusion that independent of length, since center of the pendular motion remains the same, the angles have small differences maximize distance traveled.

Uncertainty

The uncertainty for each combination of launch angle and radius can be found by subtracting the minimum value from the maximum value in the trials and then dividing by 2. Thus, the data with the uncertainties for the average is as follows:

Launch Angle ±2 (degrees)	Length ±0.0005 (m)	Distance ±0.0005 (m)			Theoretical (m)	Average (m)[16]	Uncertainty[17]
		Trial 1[18]	Trial 2	Trial 3			
0	1.000	1.591	1.587	1.602	1.4199	1.593	± 0.0073
0	0.800	1.644	1.560	1.578	1.5009	1.594	± 0.042
0	0.600	1.528	1.573	1.542	1.4730	1.548	± 0.023
15	1.000	2.158	2.109	2.264	2.2159	2.177	± 0.077
15	0.800	2.139	2.223	2.103	2.0961	2.155	± 0.060
15	0.600	2.206	1.940	2.153	1.8885	2.100	± 0.13
30	1.000	2.406	2.524	2.247	2.7400	2.392	± 0.14
30	0.800	2.398	2.226	2.160	2.4304	2.261	± 0.12

[14] These values were found by plugging the functions into a graphing calculator and then mathematically determining where the derivative equals 0. The output had a significantly higher precision which is arbitrarily limited her for the sake of viewing and diminishing usefulness with increasing number of digits.

[15] The limitations section within the Conclusion (page 13) of this investigation goes into more detail on why prevision to the exact number degree was not possible and why the uncertainty for the launch angle in the data tables is so high.

[16] The average is reported with 3 decimal places although there were more decimal places – I used the full 4 decimal place values from each trial to calculate the averages. This is done independent of the number of decimal places for uncertainty as that varied too widely and would significantly remove precision of the averages.

[17] Uncertainty for the averages is reported to 2 significant figures; this has no impact on the reporting of averages.

[18] Each trial has 3 decimal places although the ruler could measure up to 4 decimal places; however, I removed one last digit as I felt it was too precise. I did use the value with 4 decimal places for other calculations to maintain precision of those as well.

30	0.600	1.976	2.023	2.140	2.0680	2.046	± 0.082
45	1.000	2.495	2.689	2.537	2.6897	2.574	± 0.097
45	0.800	2.582	2.476	2.289	2.3068	2.449	± 0.15
45	0.600	1.559	1.372	1.685	1.8955	1.539	± 0.16
60	1.000	1.850	1.893	1.794	2.1294	1.846	± 0.049
60	0.800	1.567	1.983	1.974	1.7886	1.842	± 0.21
60	0.600	1.354	1.226	1.098	1.4342	1.226	± 0.13

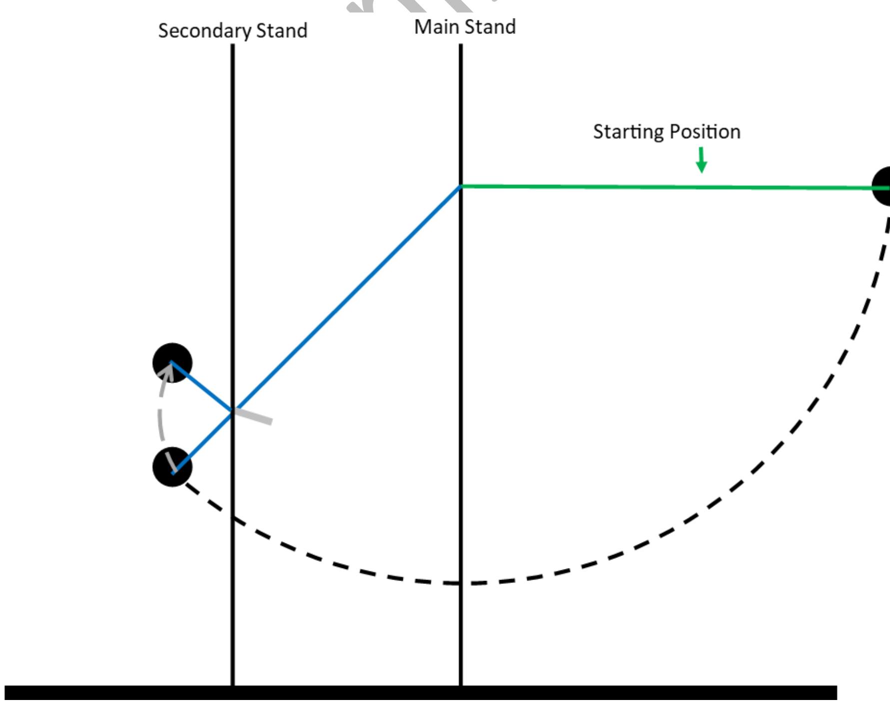
The uncertainty is significantly higher for some launch angles compared to others, namely for the higher launch angles. This makes sense, since there is more fluctuation when it comes to the blade accurately cutting the string to release the rock. The rock also must swing further, which made it more difficult to aim the rock towards the carbon paper and probably adjusts how far it goes. Additionally, any horizontal movement by the rock went unaccounted in terms of distance, which not only made the rocks go shorter but also increased the uncertainty between data trials as well.

Conclusion and Limitations

My original hypothesis has been disproven in this lab experiment. The exact ideal angles are 36.219, 33.642, and 30.396 degrees for lengths of 1, 0.8, and 0.6 meters. Further, while the data collected from the experiment did not line up perfectly with the expected results, it is somewhat close.

Unfortunately, the uncertainty and error is higher than I would have liked for a variety of reasons.

When the string is cut by the blade, it is not like when Spider-Man opens his hand to let go of his web. Rather, due to the tension of the string, it begins to swing upward and then release when it finally breaks, as depicted in the diagram below by the gray, dashed arrow[19]:



[19] The impact on this limitation is hyperbolized for the sake of simplicity and comprehension – the tension in the string was not strong enough to the point that the ball actually went backward when being released.

A possible solution to this limitation would be to use string of a lower tension so that it would break easier. While this would reduce the chances of there being a secondary swing as shown above, it would also make the string much more fragile. I used the thinnest string available to me, but it still had a decent amount of tension.

A second part to this limitation that greatly affected the process by which I collected my data is the difficulty posed by lining up the angle. Even though my procedure attempted to take caution against it, the uncertainty for the launch angle is quite significant because of small adjustments. The blade would move slightly to the left and right when the rock was swinging and even using the protractor was quite difficult in ensuring an absolutely correct degree with a very small uncertainty. Further, doing the trials for these instances alone took a significant amount of time (approximately 10 hours to collect data), rendering it quite difficult to collect data in one-degree intervals even if it was possible. Additionally, the variations between individual degrees such as between 30 and 31 degrees is extraordinarily small, rendering any investigation results with the current uncertainties almost certainly useless. Better equipment to get even more precise would be the easiest solution, although somewhat impractical for my current situation considering that I did this experiment in a high school laboratory.

Another limitation regarding the experiment is that horizontal distance is not accounted for in both the trajectory of the object and the release point procedure. While every attempt to ensure that the rock was moving in a perfectly straight pattern parallel to the reference tapes on the ground used to measure and collect data, there is still a chance that even the slightest waver in how the rock is released can affect its path. A possible solution to this limitation would be to create a jig that released the rock in the same way every time in a more open area such that the measurements would happen in one plane, ignoring the horizontal movement of the rock.

Finally, one last limitation with the experiment is that the center of the pendulum's motion remained the same while the length changed. In the original inspiration for the experiment, Spider-Man is in a fixed location, with changing heights based on how high he shoots his web. In this case, that would mean that the rock would be close to the same height, although the starting position would have to be less than 90 degrees for this to make any substantial difference. A solution to this would be to adjust the center of the main stand each time, although that could prove quite tedious in collecting data.

Overall, I was delighted by the process of planning, experimenting, and then reflecting throughout this paper. I am satisfied that I know now how Spider-Man can optimize his swinging by analyzing pendulum motion.

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[20] Every photo was either created originally or taken firsthand – thus, there are no citations for any of the photos.