The Physics of Bungee Jumping: An Exploration of the Effect of Changing Bungee Cord Length on Maximum Return Velocity

"Within an isolated system, energy may be transferred from one object to another or transformed from one form to another, but it cannot be increased or decreased; created or destroyed."

This is a quote by German physicist Julius Mayer who was the first person to state "*The Law of the Conservation of Energy*" in a simple, 1842 scientific paper.

§1. "Simplicity is key."

The law of conservation of energy is a testament to the desire of all physicists to achieve ultimate simplicity in a universe of elegance and messiness.

Thanks to history, even a simple-minded teenager like me today can appreciate the splendor of years of complex thought and experimentation through my school physics textbook and hope to uncover the truths about this miracle child of classical physics.

Although it may seem trite and cliché, every time I have flipped through my *Pearson Physics* textbook this past school year, I felt a natural attraction towards the unit on mechanical energy. Aside from the enthralling visual graphics and in-the-moment photographic images, what stood out to me the most was the simplicity and novelty in the demonstration of the physics concepts. In other words, I thought it was simple and neat. As I explored the topic further through school assignments and my own design labs, it soon apparent that this was my favorite topic. Who knew learning about *The Law of Conservation of Energy* (Pearson, pg. 312) could be so interesting? It was as if I had seen "true" physics for the first time, and it was a breath of fresh realization.

Physics isn't about big words or fancy theories; it's about being accurate and simple.

Staying true to my own words, I decided to investigate the physics of bungee jumping when choosing the topic for my IA. Specifically, my research question asks, "What is the effect of lengthening a bungee cord on the maximum return velocity of the bungee jumper?"

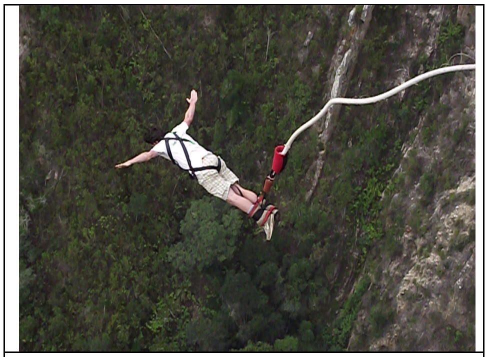
This exploration will show how altering the length of a bungee cord will also change how fast a bungee jumper is pulled back up by the cord. In recreational bungee jumping, jumpers may each have different lengths of bungee cord, and that can greatly affect the return velocity of their jump. It will also change how much more exhilarating the ride will be! Obviously, the faster you go, the more exciting it is!

§2. The Death-Defying Leap of Faith: Bungee jumping

Thrill, adrenaline, and terror. These are the often-used words to describe bungee jumping. Imagine hurtling through the air at the speed of an automobile, your ears ringing, your body aching with every blast of forceful wind threatening to knock you unconscious. Then again, imagine the thrill! You have just defied death and you are ready to do it again!

This time around, you try a different kind of jump. The first one you tried was a **railing jump;** you balance yourself on the edge of the railing to gain extra height, then you let someone push you off the ledge. This time, you decide to be mainstream and try the **swallow dive.** Mustering all of your stored up courage, you leap off the edge, arms outstretched as you soar like a free swallow diving towards the earth…

To read more about "types of bungee jumps", use the following link: [http://www.bungeezone.com/types/]



"I'm free!"
http://macsledger.blogspot.ca/2011/03/bungee-jumping.html

§3. Social and Historical Dimensions

Classified as an "extreme" sport, bungee jumping is notoriously known for the sensational, near-death shock experience that it provides. But it wasn't always a sport. Legend has it that there lived a young woman and her abusive husband Tamalie in the native villages of Pentecost Island, South Pacific Ocean. One day, Tamalie was chasing his wife around the island when suddenly she climbed up the top of a tall tree. He climbed after her, and when they both reached the top, he reached out to grab her but ended up falling to his death. It turns out the young woman had tied lianas onto her ankles before hand so that she would survive the fall. Her husband? Not so lucky.

And so it was that bungee jumping became a tradition in the native villages of Pentecost Island. Today, bungee jumping is considered both a recreational and competitive sport with enhanced safety precautions and bungee cords designed to give you the ride of your life!

To read more about the exciting sport:
"The history of bungee jumping" by Hlede [http://www.bungee.com.hr/en/history]

§4. The Law of Conservation of Energy

In a cash transaction between two people stationed in a closed office room, money can flow between them limitless times but the total amount of money after the transactions will always be equal to the total amount of money prior to transaction. This is considered an **isolated system**. However, if a transaction were to be completed with someone outside of the office, the total amount of money in the office before and after transaction system would no longer be equal. This is considered a non-isolated system. For simplicity's sake, if a system needs to be analyzed in terms of its ability to conserve energy, it should be thought of as an isolated system.

The Law of Conservation of Energy states that *"Within an isolated system, energy may be transferred from one object to another or transformed from one form to another, but it cannot be increased or decreased; created or destroyed. This is the Law of Conservation of energy"* (Pearson Physics Textbook, pg. 312-313).

In mathematical form, this is represented by the formulas:

1. $E_{mechanical\ 1} = E_{mechanical\ 2}$

2. $\boldsymbol{E_{mechanical}=E_{kinetic}+E_{potential}}$

In other words, in any isolated system, a gain in either kinetic or potential energy must be accompanied by a simultaneous loss in potential or kinetic energy, respectively. Furthermore, **the total mechanical energy at all locations within the system must be equal.**

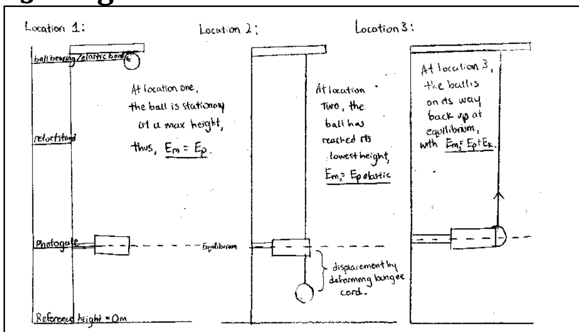
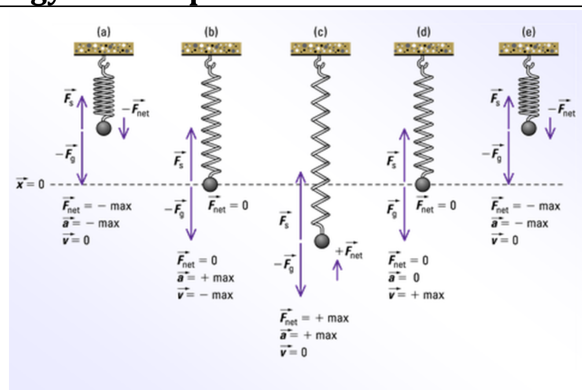
The closest a bungee-jump system can get to being an isolated system is during the first full oscillation: a full path down, then back up again. During this oscillation, we can assume that all energy is conserved anywhere along the path of the jump. Therefore, it is possible to compare and equate the total mechanical energy at different locations, whether they are in the form of kinetic, or potential energy.

According to the law of conservation of energy the mechanical energy at location one of the jump is the same as the mechanical energy at locations two and three of the jump. (See figure 1 for further details).

Comparing location 1 and 3, $E_{m1} = E_{m3}$

Thus $E_{p1} = E_k + E_{p2}$ And $mgh_1 = 0.5mv^2 + mgh_2$ (*Pearson Physics Textbook formulas*). The formula relating maximum return velocity to elastic band length then, is $\vec{v} = \sqrt{2g(h_2 - h_1)}$, where the difference of heights is equal to the length of elastic band, $l_{elastic}$. Thus the formula for velocity is: $\boldsymbol{\vec{v} = \sqrt{2 * g * (l_{elastic})}}$, where v α $\sqrt{l_{elastic}}$.

§5. Figures 1 and 2: Conservation of energy and Simple harmonic motion

	
"Conservation of energy in a bungee system."	**"Simple Harmonic motion."** http://physics20project.weebly.com/unit-5-oscillatory-motion-and-mechanical-waves.html

§6. Simple Harmonic motion: Maximum Velocity and Restoring Force

The reason I decided to measure the velocity of the ball bearing at the equilibrium position is due to my understanding of the principles of simple harmonic motion. Specifically, the elastic bungee system in my experiment is comparable to the simple harmonic motion of a vertical mass-spring system.

As illustrated by figure 2 above, the force of tension on a vertical and frictionless mass-spring system varies according to the position of the mass relative to the equilibrium line (dotted line). In all of these cases, the net force acting on the mass spring is called the **restoring force** and "*For any frictionless simple harmonic motion, the restoring force is equal to the net force*" (Pearson Physics textbook, pg. 356).

Evidently, the restoring force is at a maximum when the displacement of the mass is at a maximum. This is also where the mass will have the greatest acceleration in the direction of the restoring force. On the contrary, where the restoring force is equal to zero at the equilibrium position is where the mass has a **maximum velocity** after it has accelerated fully.

These principles can be applied to my elastic bungee system since the elastic band I used, without changing its shape or material strength, represented a harmonic oscillator for its first oscillation, where friction was assumed to be negligible. In addition, based on case d) of figure 2, my elastic bungee system also had a net restoring force of zero at its equilibrium position and a maximum velocity in the upward direction.

§7. Kinematics: Velocity

Velocity is defined as an object's displacement traveled in a certain time, and represented by the formula:

$$\vec{v}_{ave} = \frac{\Delta \vec{d}}{t} \text{ (\textit{Pearson Physics Textbook pg. 12})}$$

The maximum return velocity variable in this experiment will be determined using this formula.

§8. Model and design: My simple method

My method of modeling a bungee jump involved combining certain aspects of the Hooke's law lab I completed in Physics 20IBSL, and the free fall lab I completed in Physics 25 IB. The main idea was to attach a metal ball bearing to an elastic band fixed to a certain height, and drop it from that controlled height above the ground. Since the elastic band was stretchable and stored elastic potential energy, it pulled the ball bearing back up after the ball reached the lowest height in its path. I then calculated the velocity of the ball bearing as the ball moved past its equilibrium position by determining the duration of time it took the ball to move through a Photo gate sensor, and using the velocity formula mentioned in section 6. Then, as mentioned in section 5, I examined the ball bearing as it passed through the equilibrium position with a maximum velocity, which changed depending on the initial length of the elastic band.

In this experiment, I manipulated the length of the elastic band by shortening it approximately 0.010 meters each manipulation. (See page 1-2 in supporting documents for more details).

§9. Assumptions

The major assumptions for the elastic bungee system in this experiment are:

1. The system is isolated for the first oscillation of the elastic band and ball bearing.
2. There are no external net forces acting on the system besides gravity, friction in the elastic band is negligible, and energy is conserved throughout the system.

§10. Scientific hypothesis

If the length of a bungee cord is shortened, then the maximum return velocity of the jumper will also decrease because according to the law of conservation of energy, the maximum return velocity of the jumper at equilibrium is proportional to the square root of the initial length of the bungee cord: $v \propto \sqrt{l_{elastic}}$.

§11. Safety, Environmental and Ethical concerns

Safety: Major safety concerns in this lab include the risk of moving projectiles such as ball bearings or elastic bands potentially striking students, the risk of equipment falling over and smashing feet, and the risk of self-inflicted harm when proceeding to use cutting utensils. To avoid these risks, tie all elastic bands tightly, make sure not to throw objects around while experimenting, and cut away from yourself or other experimenters. The experimenter should stay always stay cautious of moving projectiles and falling objects in the laboratory, and take precautionary measures such as wearing aprons, goggles, or other protective gear if necessary.

Environmental and ethical: There are no ethical issues or concerns pertaining to this experiment. Environmental issues are concerning the proper disposal of equipment: all elastic bands will be recycled after usage.

§12. Observations table: Basic raw data

Table 1. Change in the time taken for a metal ball bearing attached to an elastic band to travel through its equilibrium position and travel its diameter.

Length of elastic band, $l_{elastic}$, (±0.05cm)	Displacement of ball bearing, d_{ball}, (±0.05cm[up])	Time, t_{ball}, (±0.00001s)				
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
68.70	2.44	0.00628	0.00651	0.00700	0.00692	0.00685
58.75	2.44	0.00659	0.00663	0.00642	0.00651	0.00720
44.50	2.44	0.00801	0.00759	0.00762	0.00810	0.00803
33.50	2.44	0.01210	0.01312	0.01260	0.01305	0.01298
16.56	2.44	0.01503	0.02096	0.01690	0.01701	0.01826

Qualitative

- There are a few deformities on the elastic band surface, however not enough to affect measured values. Loose ends pass through the photogate sensor, but don't affect the time values of the ball bearing. Each equilibrium point / line is above the previous, and the ball bearing is stationary at those locations. Figures of the experimental data will show this.
- Ball bearing is a perfect metal sphere with no cavities, indentures or deformities.
- Rubber/elastic band is very stretchy and thin, but strong enough to support the weight of the ball bearing without breaking or deforming.

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§13. Unit conversions and averaging time values with absolute uncertainty

To determine the maximum return velocity of the ball bearing, which was the original objective of this experiment, I first converted the values for the displacement of the ball bearing, and lengths of the elastic band from centimeters (cm) to meters (m). Then I averaged the time values for each manipulation of length since these replicates had very similar values. The following illustrates sample calculations for the unit conversions as well as the averaging method used for the time values of elastic band length 68.70cm. I used the same unit conversion method for displacement values.

Convert centimeters (cm) to meters (m): $68.70cm\left(\frac{1m}{100cm}\right)$= 0.6870m

To average time (s) values, I calculated the arithmetic mean of the 5 trials.

$t_{ball\ average} = (t_{trial\ 1} + t_{trial\ 2} + t_{trial\ 3} + t_{trial\ 4} + t_{trial\ 5})\ (\frac{1}{5})$

$= (0.00628s+0.00651s+0.00700s+0.00692s+0.00685s)\ (\frac{1}{5})$

$= 0.006712s$

$\approx 0.00671s$

Next, I considered the absolute uncertainty of the converted values. For length and displacement values, the relative uncertainty of the unconverted values was multiplied by the converted values and hence displayed four decimal places after conversion, as expected. However for the averaged time values, the uncertainty in the final averaged time had to be considered by halving the range between the largest and smallest time values. This is illustrated below.

Uncertainty in elastic band length: (68.70cm±0.05cm) hence,

$$(\frac{0.05cm}{68.70cm})(0.6870m)=\pm0.0005m$$

Uncertainty in averaged time values:(t_{max}=0.00700s t_{min}=0.00628s)

$$(\frac{Range}{2}) = (\frac{0.00700s-0.00628s}{2}) = \pm0.00036s\approx\pm0.0004s$$

§14. Data Table of converted units and averaged time values

Table 2. Average time taken for a falling metal ball bearing attached to an elastic band to travel through its equilibrium position and travel its diameter

Length of elastic band, $l_{elastic}$, (±0.0005m)	Displacement of ball bearing, $\vec{d}_{ball}$, (±0.0005m[up])	Average time, $t_{ball\ average}$, (±0.0004s)
0.6870	0.0244	0.0067
0.5875	0.0244	0.0067
0.4450	0.0244	0.0079
0.3350	0.0244	0.0128
0.1656	0.0244	0.0176

§15. Determining the maximum return velocity of the ball bearing

Next, I used the kinematics equation described in section 6 to determine the maximum return velocity of the ball bearing, in ($m*s^{-1}$ [up]).

Calculating the maximum return velocity of the ball bearing ($m*s^{-1}$ [up]):

$v_{ball\ max} = (d_{ball})*(t_{ball\ average})^{-1}$

$= (0.0244m)*(0.006712s)^{-1}$

$=3.6363636363\ m*s^{-1}$ [up]

$\approx 3.63\ m*s^{-1}$ [up]

To consider percent and absolute uncertainty in the maximum velocity values, I determined the sum of the relative uncertainties of the displacement and time values and then multiplied the percent uncertainty by the original velocity value. *Note: I will be using unrounded values in my calculations, but I will still carry on significant digits in the final answers.

Relative uncertainty in displacement:
(0.0244±0.0005m [up]) hence $\left(\frac{0.0005m_{[up]}}{0.0244m_{[up]}}\right) * 100$=2.23214286%≈2%

Relative uncertainty in averaged time values:
(0.0067±0.0004s) hence $\left(\frac{0.0004s}{0.0067s}\right) * 100$=5.97014925%≈6%

Percent uncertainty in maximum return velocity:
(2.23214286%+5.97014925%)=8.202292114%≈8%

Absolute uncertainty in maximum return velocity:
(8.202292114%)(3.635280095m*s^{-1}[up])=±0.2981762926m*s^{-1}[up]≈±0.3m*s^{-1}[up]

<u>§16. Data table of calculated maximum return velocity and uncertainties</u>

Table 3. Maximum return velocity of a falling metal ball bearing attached to an elastic band as a result of decreasing the length of elastic band

Length of elastic band, $l_{elastic}$, (±0.0005m)	Maximum return velocity of ball bearing, $v_{ball\ maximum}$, (m*s^{-1} [up])	Absolute uncertainty in velocity (m*s^{-1} [up])	Relative uncertainty in velocity (%)
0.6870	3.6	±0.3	8
0.5875	3.7	±0.3	8
0.4450	3.1	±0.2	7
0.3350	1.9	±0.1	5
0.1656	1.4	±0.1	4

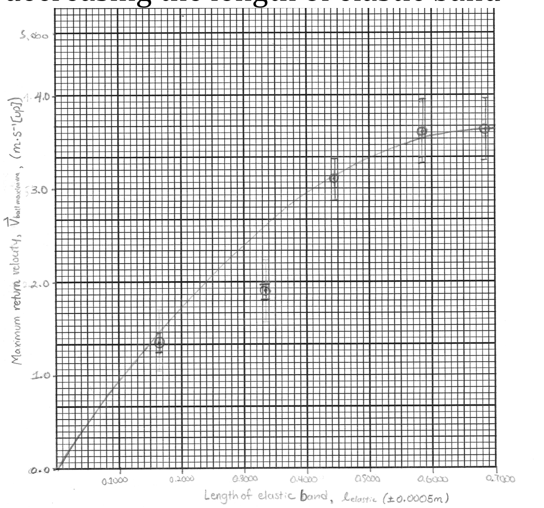
Evidently, all data values are decreasing down their respective columns, and most notably, the accompanied decrease in maximum return velocity as length of elastic band shortens supports the part of the hypothesis stating, *"If the length of a bungee cord is shortened, then the maximum return velocity of the jumper will also decrease."*

Both the relative and absolute uncertainties present in the maximum velocity values range from large to small as the length of elastic band decreases. This trend was to be expected as shorter lengths of elastic band traveled a shorter path in this experiment, and there was less opportunity for the ball bearing to sway in its path and create measurement uncertainties. Consequentially, shorter lengths of elastic band produced more consistent time values with less uncertainty.

§17. The square-root curve

At this point in my analysis, I decided to refer back to my hypothesis in order to justify my immediate assumption of a square-root relationship between length and velocity. My assumption was based on my observation that the maximum return velocity values seemed to be decreasing at the same constant rate as the length values. With further knowledge that the ball bearing would have a maximum return velocity of 0 m*s^{-1} [up] if the length of the elastic band were 0 m, I assumed that there would also be a y-intercept if this relationship were graphed.

Figure 3. Maximum return velocity of the falling ball bearing as a result of decreasing the length of elastic band



By looking at this graph, it clearly resembles a square-root relationship, with the line of best fit having a gradually decreasing slope and passing through the origin. The peculiar second data point is most likely due to the deformity of the elastic band, which had been slightly worn out when I tested the length of 0.3350m. When I observed the elastic band during experiment however, I did not notice it wearing out or slightly deforming and that was my mistake.

§18. Straightening the square-root curve

Next, I employed curve-straightening techniques by squaring the y-axis values based on my assumption of a square-root relationship. If the assumption of y is proportional to √x is true, then the graph of y^2 and x should display a proportional relationship with no y-intercept. Shown below is a sample calculation squaring the maximum return velocity value for elastic band length of 0.6870m.

Squaring maximum return velocity values:
(3.635280095 m*s^{-1} [up])^2= 13.21526137 m^2*s^{-2}≈13 m^2*s^{-2}

Since only mathematical manipulation is required to straighten the curve, I represented the percent uncertainty of the squared maximum return velocity values as the percent uncertainty of the original velocity values. However, to determine the absolute uncertainty in squared velocity values, I multiplied the percentage error with the squared values as below.

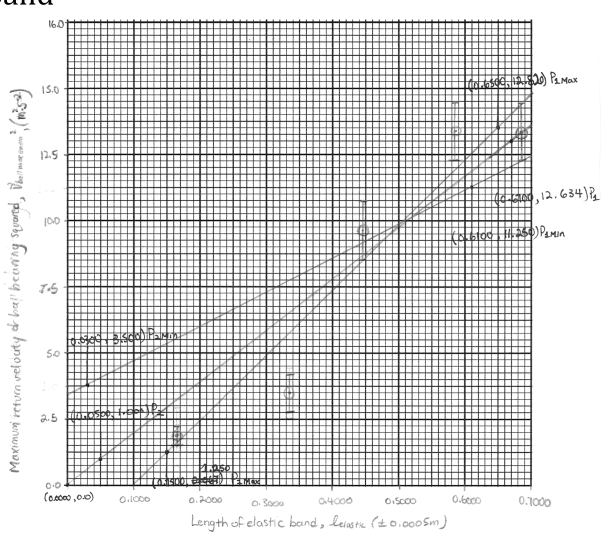
Absolute uncertainty in squared return velocity:
$(8.202292114\%)*(13.21526137\ m^2*s^{-2})=\pm1.083954341 m^2*s^{-2} \approx \pm1\ m^2*s^{-2}$

Table 4. Maximum return velocity squared in relation to the length of the elastic band with absolute and relative uncertainty

Length of elastic band, $l_{elastic}$, (±0.0005m)	Maximum return velocity of ball bearing squared, $v_{\text{ball maximum}}^2$, ($m^2*s^{-2}$)	Absolute uncertainty in squared velocity (m^2*s^{-2})	Relative uncertainty in squared velocity (%)
0.6870	13	±1	8
0.5875	13	±1	8
0.4450	10	±1	7
0.3350	4.0	±0.2	5
0.1656	2.0	±0.1	4

*Note: Since my precision restraint on the absolute uncertainty cannot accommodate all decimal places of the values in the last two rows of this data table, I have decided to allow one decimal place in these uncertainty values so that the uncertainty for the last two rows of data can be graphed accordingly.

Figure 4. Maximum return velocity of the ball bearing as a result of decreasing the length of the elastic band



After squaring the maximum return velocity values, and graphically representing the data in figure 4, I made the **second assumption** that the result in figure 4 was a **proportional relationship**. Hence, I drew the line of best fit as a straight line connecting the origin to the last data point, with two points above and below the line using the “relative accuracy by eye” technique. I could have interpreted the graph as a square root relationship, or even a power relationship due to the curve of the data at the second data point, however I decided to continue following my hypothesis.

For the minimum and maximum lines I decided to neglect the second peculiar data point for the same reasons as I did with the line of best fit, and drew the lines so that they accommodated error bars for 3 of the remaining data points. The reason I chose the last data point as a reference to draw the min/max lines is because my data represents more accuracy than consistency in the velocity values, and having the min/max lines in close proximity to the line of best fit best reflects this. Overall, the same trend in uncertainty can be seen in this graph as in the last one- the error bars range from large to small as the length decreases. This doesn't change even after I squared the velocity values.

§19. Equation of the line

To finally determine the relationship between maximum return velocity and length of elastic band, I calculated the equation of the line of best fit in figure 4 using three points on the line. The points used were the following:

For slope calculations,
[P1, P1 $_{max}$, P1$_{min}$]: [(0.6700m, 12.634 m^2*s^{-2}), (0.6500m, 12.820 m^2*s^{-2}), (0.6100m, 11.250 m^2*s^{-2})]
[P2, P2 $_{max}$, P2$_{min}$]: [(0.0500m, 1.000 m^2*s^{-2}), (0.1500m, 1.250 m^2*s^{-2}), (0.0300m, 3.500 m^2*s^{-2})]

Below is a sample calculation for determining the slope (m) of the line of best fit. I also used this technique to determine the minimum and maximum slopes.

$$m = (y_2-y_1)*(x_2-x_1)^{-1}$$
$$=(12.634\ m^2*s^{-2} - 1.000\ m^2*s^{-2})*(0.6700m-0.0500m)^{-1}$$
$$=18.76451613\ m*s^{-2}$$
$$= 19\ m*s^{-2}$$

After determining the slope of the lines I determined the range in slope, or error in slope, by taking the range of the maximum and minimum slopes, then halving it. Denoted by Δm, this value represents the possible deviation in slope value.

$$m=18.76451613\ m*s^{-2}$$
$$m_{max}= 25.14000000\ m*s^{-2}$$
$$m_{min}= 13.36206897\ m*s^{-2}$$
$$Range= 11.77793103\ m*s^{-2}$$
$$\Delta m=\pm\frac{Range}{2}= \pm 5.888965515\ m*s^{-2}$$
$$m\pm \Delta m=19\pm 6\ m*s^{-2}$$

Therefore, the **equation of the line** in the form *y=mx*, passing through the origin is: $\vec{\boldsymbol{v}}_{\boldsymbol{ball\ max}}{}^{\mathbf{2}} = (\mathbf{19} \pm \mathbf{6}\ \boldsymbol{m} * \boldsymbol{s}^{-\mathbf{1}}) * \boldsymbol{l}_{\boldsymbol{elastic}}$

§20. Comparing gravitational field strengths

Finally, to justify my results with an accepted scientific context, I decided to compare my experimental value for gravitational field strength with gravitational field strength values at three different nearby locations in Alberta. These values are given by: [SensorsONE Ltd. (2016). "*Local gravity calculator*". Retrieved January 06, 2015 from: http://www.sensorsone.com/local-gravity-calculator/].

I used the equation $\vec{\boldsymbol{v}} = \sqrt{\mathbf{2} * \boldsymbol{g} * (\boldsymbol{l_{elastic}})}$ described in section 4 to isolate the g variable, and then used the slope value to determine the experimental gravitational acceleration.

Rearranging the formula to solve for experimental g,

$$\vec{g}_{exp} = \frac{(\vec{v}^2) * (l_{elastic})^{-1}}{2} = \frac{slope}{2} = \frac{18.76451613\ m * s^{-2}}{2} = 9.382258065\, m * s^{-2}$$

$$\vec{g}_{exp} = 9.4\, m * s^{-2}$$

Table 5. Comparing gravitational accelerations at different locations with $g_{experimental}$

Location	Latitude (°)	Height above sea level (m)	Value of g ($m*s^{-2}$)	Percent difference (%)
Calgary	51	1042	9.80838	4.2
Edmonton	53	610	9.81147	4.5
Banff	51	1383	9.80733	4.4

<u>Sample calculation: percent difference for Calgary</u>

% diff=$100*|g_{experimental}-g_{theoretical}|*[0.5*(g_{experimental}+g_{theoretical})]^{-1}$
$=100*|\ 9.38226m*s^{-2}-9.80838m*s^{-2}|*[0.5*(9.38226m*s^{-2}+9.80838m*s^{-2})]^{-1}$
$= 4.210526316\%$
$\approx 4.2\%$

§21. Conclusion

By applying the physics principles of the law of conservation of energy and simple harmonic motion to this model of a bungee-jumping system, I was able to derive a formula relating the maximum return velocity of the ball bearing to the length of the elastic band that suspended it. This formula formed the basis for my hypothesis, predicting the relationship as $v \propto \sqrt{l_{elastic}}$. Then, through data manipulation and curve straightening techniques, I determined the equation of the relationship $\vec{\boldsymbol{v}}_{\boldsymbol{ball\ max}}{}^{\mathbf{2}} = (\mathbf{19} \pm \mathbf{6}\ \boldsymbol{m} * \boldsymbol{s}^{-\mathbf{1}}) * \boldsymbol{l_{elastic}}$ where $\vec{v}_{ball\ max}{}^{2} \propto l_{elastic}$ and equivalently $\vec{v}_{ball\ max} \propto \sqrt{l_{elastic}}$. This equation justifies the stated hypothesis: "*the maximum return velocity of the jumper at equilibrium is proportional to the square root of the initial length of the bungee cord.*"

Furthermore, my results comparing the experimental acceleration of gravity to different theoretical values were satisfactory and showed that the experimental acceleration had the least percent error of 4.2% when compared to Calgary, which is the very place I conducted the experiment. Overall, all of the percent error values were <5%, indicating that this experiment could potentially be applied to real life bungee jumping in Calgary.

§22. Evaluation

The major sources of error in this experiment that **I overlooked when making qualitative observations** were: the ball bearing was gradually deforming the elastic band, and the ball bearing swayed slightly in its path during most of the trials.

The ball bearing was gradually deforming the elastic band as the experiment proceeded, causing latter time values to be less accurate and too low. Specifically, this caused a major, systematic and mechanical error that caused velocity values for all lengths, but especially for elastic band lengths of 0.3350m, and 0.1656m, to be lower than expected, hence the first few data points of figures 3-4. This is also the reason for the peculiar second data point that I neglected in the analysis. To improve on this aspect of the experiment, next time an elastic band with a higher k constant and therefore a stronger elastic band, can be used so that it can support the mass of the ball bearing without deforming.

Another major error in this lab was the swaying of the ball bearing on its downward path. Overall, this side movement caused some energy to be lost and not transferred to the ball bearing as it made its way back up. This was a major, random, and procedural error that caused all recorded time values to be higher than expected. Consequentially, this caused the velocity values of the two largest lengths to be higher than expected, hence the last two data points of figures 3-4. To fix this error for next time, avoid performing the experiment in ventilated rooms, and possibly use a clamping mechanism to hold and release the ball bearing instead of using hands.

The **greatest strength** of my experiment is simplicity. Only three variables need to be tested or measured; these are length, displacement, and time. Furthermore, the square-root graphical relationship between velocity and length only requires two steps of mathematical manipulation in order to obtain a meaningful equation of the line of best fit. Another strength is having a practical method to evaluate the experimental g value at locations where the experiment may be performed. As my percent error in Calgary was only 4.2%, this experiment may prove to be applicable to real life in this respect.

As highlighted by the sources of error, the **greatest limitation** to this experiment was the fact that the materials used were slightly impractical, such as the weak and thin elastic band, which was not practical to use with a heavy metal ball bearing. Ideally, the elastic band should have been stronger with a higher k constant so that it can actually support the ball bearing without deforming even slightly. Consequentially, this means that in terms of applying this exact modeling of a bungee jump to real life would be difficult. For example, a ball bearing and an elastic band are far from actual bungee jumpers and bungee cords.

The End: So, lengthen your rope, spread your arms like a sparrow and stare death in the face as you leap off the edge of a skyscraper. The sky's the limit! (Or in this case it's the earth).

Figure 1. Bungee system apparatus	Figure 2. Equilibrium, elastic length 1

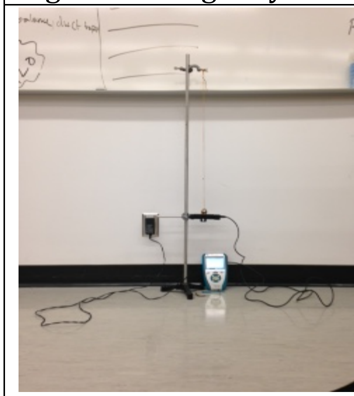
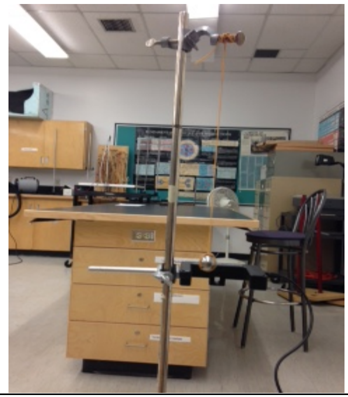

	

Figure 3. Equilibrium, elastic length 2	Figure 4. Equilibrium, elastic length 3

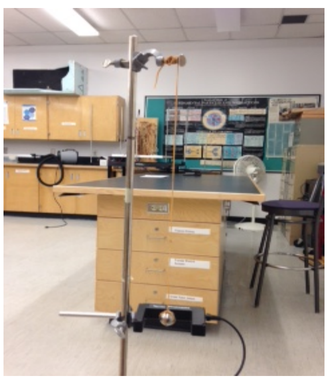
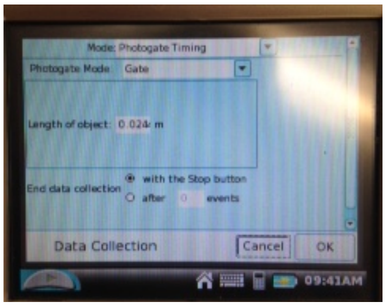



Figure 5. Equilibrium, elastic length 4	Figure 6. Equilibrium, elastic length 5
	

Variables

Manipulated variable: Length of the elastic band, $l_{elastic}$, (m).
Responding variable: Time taken for ball bearing to travel through its equilibrium a displacement equal to its diameter in its rebound path upward, t_{ball}, (s).
Controlled Variables: Diameter of ball bearing, mass of ball bearing, initial height of ball bearing prior to being dropped, type of elastic band used (spring constant).

Procedure



Set up Vernier LabQuest as shown on the left

Performing the experiment

1. Measure the diameter of the metal ball bearing using a Vernier Caliper and record this value in "displacement of ball bearing" column of the observations.
2. Place a retort stand on the ground.
3. Tie one end of the one-meter long rubber band onto the top of the retort stand with a retort stand clamp and the other end onto a metal ball bearing. Make sure that the ball bearing and elastic band both hang off the retort stand and are perpendicular to the ground.
4. Measure the distance from the top of the retort stand to the bottom end of the ball bearing and record this value under "length of elastic band" column in the observations table.
5. Using a retort stand clamp, clamp the Photogate sensor onto the retort stand and adjust it so that the sensor is just below the ball as shown in figure 1.
6. Holding the ball bearing at level with the top of the retort stand, let the ball drop through the sensor and return back up to obtain two readings for time. Record the second time value in the observations table under the "time" column.
7. Repeat steps 5-6 for 5 trials of each of 5 replicates, shortening the rubber band by 0.010 meters every time.

Shortening the elastic band

8. To shorten the rubber band, untie the rubber band from the apparatus and cut it 5 cm shorter, then tie it back as described in step 3.
9. Make sure that after shortening the elastic band, the retort stand clamp and Photogate sensor are adjusted according to step 5.