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IAR Physics Rube Goldberg Machine Report

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ABSTRACT. *This virtual Rube-Goldberg machine contains and demonstrates seven principles of physics over a time span of at least 14 seconds: elastic collision, inelastic collision, torque, conservation of energy, conservation of momentum, and projectile motion in two dimensions. In the simulation, air resistance is negligible, and gravity is constant, which means circular motion is constant as well. The purpose of this machine is to topple an egg in the final step. My machine demonstrated the seven principles of physics and was successful in its purpose as it functioned smoothly. In the end, the entire process has exceeded 14 seconds.*

KEYWORDS: *methods, Physical Steps, Analysis,IAR, virtual Rube-Goldberg Machine.*

Introduction

The task given by Professor Kelly was to create a virtual Rube-Goldberg Machine on the Blender application. The machine has to clearly show the seven principles of physics we learned in class. Since I was using Blender, there was no limits to the size or area. The objects I used can be as weirdly shaped as possible and the design can be unrestrained. Additionally, the machine has to last at least 14 seconds to perform all the steps so that no steps will be too quick to follow. Finally, after building the machine, I have to track most of the motions and calculate the changes in energy in each step. Thus, I kept my machine rather simple and easy to follow to help me demonstrate those seven principles we learned in class and make calculations easier to do. Through the revision process, my machine broke down many times and technical issues were not uncommon. Through a series of troubleshooting and improving the design, I was able to adjust everything to collaborate with each other at the end.

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Methods

I started out by putting 5 dominos on the flat platform I created. I thought this could demonstrate momentum.

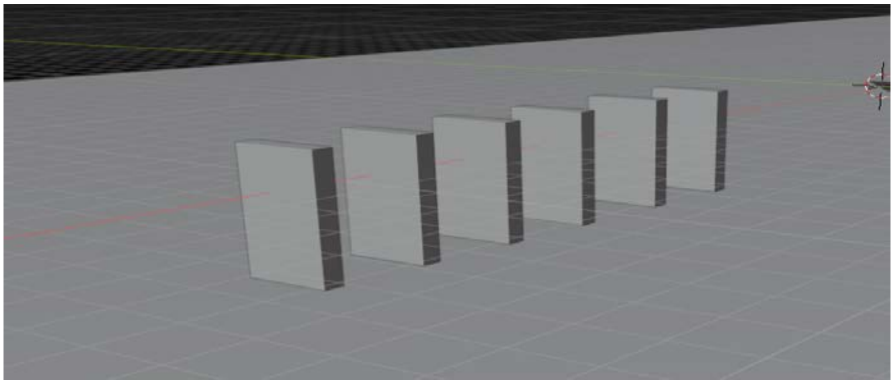

Fig. 1: Visual Representation of Initial Design:

After putting down the five dominos, I design a track for the ball to roll down and hit the first domino to start the chain reaction.

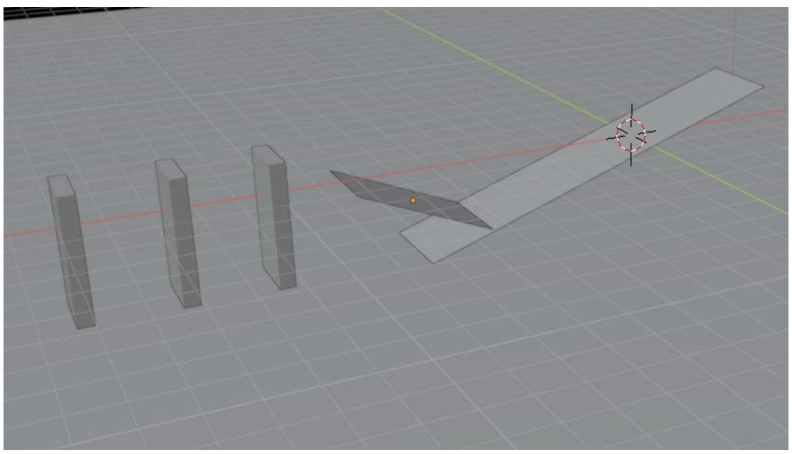

Fig.2: Adding the track

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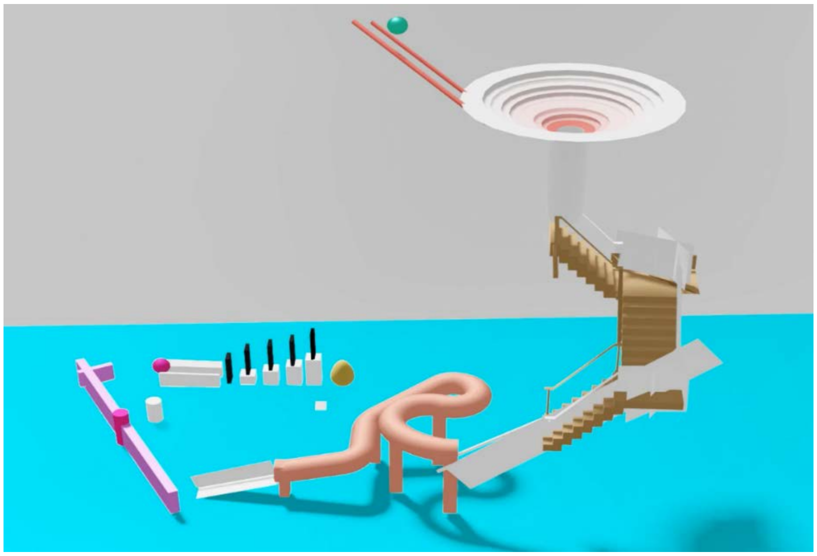

After adding the track, I downloaded a model of a slide from the internet and added it to the track so the ball can increase momentum when it goes through the slide.

Fig.3: Adding a slide

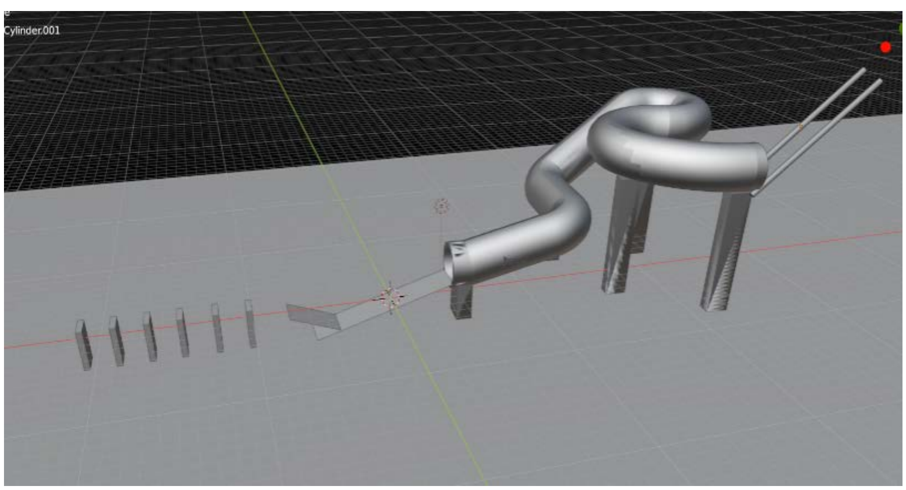

Fig.4 The final result

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After reconsidering, I put the dominos in the last step and started with circular motion. The disk, staircase, and the slide were downloaded from the internet while the other objects were design and made by me.

I analyzed the machine using an app called Tracker and record most of the moving portions. Tracker provided me with numerous graphs, which enabled me to do calculations and better analysis.

The moving parts of the machine consists of two active spheres, a vertical seesaw, 5 dominos, and the egg placed at the end. Other components of the machine are fixed on their positions.

Results

I. Description of Physical Steps

Physics Concept	Description of Step
Inelastic Collision	Collision between the pink sphere and the dominos; after the pink sphere collide with the first domino, providing it with KE and momentum, the first domino collide with the second one and the same thing happens for three times until all five dominos are down. Ideally, all KE from the pink ball would be transferred into KE of the first domino, and momentum would be conserved.
Elastic Collision	Collision between the green sphere and the vertical seesaw; initially, the green sphere is moving, and the seesaw is at rest; after the collision, the seesaw starts to spin clockwise and the ball is at rest.
Conservation of Energy	Green ball falling from the tube; this is a demonstration of conservation of energy. As the green ball falls down in the tube, it is converting GPE into KE.
Conservation of Momentum	The vertical seesaw; the green ball colliding with the vertical seesaw shows

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	conservation of momentum. Ideally, the KE of the green ball just before impact should equal the KE of the seesaw just after the impact.
Projectiles in 2-Dimensions	Green ball rolling down the staircase; the ball rolling down the stair case demonstrates projectiles in 2-Dimensions.
Rotation	Circular disks; the green rolling on the circular disks demonstrates circular motion. Due to the slope being downwards and gravitational pull, the ball starts to travel in big circular paths then slowly narrows down to smaller circular paths.
Torque	Vertical seesaw; the interaction between the green ball and the lever arm causes a torque force around the pivot at the center and results in the lever arm on the other side hitting the pink ball resting on the track.

Table 1: Outline of Steps in Rube Goldberg Machine

II. Calculations and tracker plots

III. Elastic Collision, green ball hitting the vertical seesaw

IV. Analysis of results

Key: gb= green ball, ss= vertical seesaw

In an elastic collision, energy is conserved and so $\frac{1}{2}mv_{before}^2 = \frac{1}{2}mv_{after}^2$ In addition, momentum ($p = mv$) is conserved so $mv_{before} = mv_{after}$

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$m_{gb} = 5kg; m_{ss} = 2kg$

$V_{i,gb} = \frac{1.92m}{s}; V_{f,gb} = 0$

$V_{i,ss} = 0; V_{f,ss} = \frac{2.46m}{s}$

*To calculate conservation of momentum:

$p = mV_{i,gb} = (5)(1.92) = 9.6kg * \frac{m}{s}$

$p = mV_{f,ss} = (2)(2.46) = 4.92kg * \frac{m}{s}$

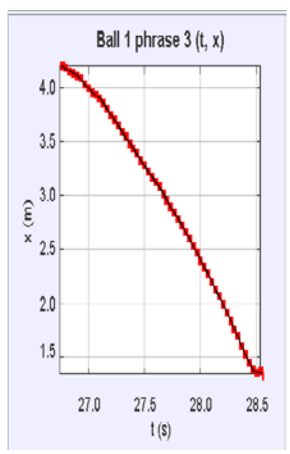
*To calculate conservation of KE

Fig.i.1 & 2, time and corresponding cartesian coordinates

t (s)	x (m)	y (m)
26.767	4.204	-8.551
26.800	4.178	-8.576
26.833	4.157	-8.607
26.867	4.137	-8.630
26.900	4.108	-8.654
26.933	4.084	-8.670
26.967	4.027	-8.720
27.000	3.996	-8.744
27.033	3.954	-8.779
27.067	3.925	-8.811
27.100	3.903	-8.836
27.133	3.861	-8.876
27.167	3.801	-8.923
27.200	3.750	-8.966
27.233	3.696	-9.014
27.267	3.647	-9.053
27.300	3.589	-9.093
27.333	3.538	-9.131
27.367	3.488	-9.157
27.400	3.436	-9.191
27.433	3.384	-9.224
27.467	3.332	-9.259
27.500	3.279	-9.296
27.533	3.226	-9.333
27.567	3.179	-9.362
27.600	3.126	-9.394
27.633	3.075	-9.418
27.667	3.017	-9.451
27.700	2.960	-9.481

27.733	2.894	-9.507
27.767	2.840	-9.545
27.800	2.786	-9.579
27.833	2.725	-9.613
27.867	2.661	-9.654
27.900	2.606	-9.690
27.933	2.537	-9.732
27.967	2.477	-9.773
28.000	2.403	-9.814
28.033	2.336	-9.860
28.067	2.274	-9.905
28.100	2.203	-9.942
28.133	2.127	-9.974
28.167	2.067	-10.02
28.200	1.994	-10.06
28.233	1.922	-10.10
28.267	1.846	-10.14
28.300	1.769	-10.18
28.333	1.693	-10.21
28.367	1.610	-10.25
28.400	1.533	-10.29
28.433	1.452	-10.33
28.467	1.382	-10.38
28.500	1.366	-10.42
28.533	1.367	-10.42
28.567	1.335	-10.48

Fig.i.3, position vs. time for green ball



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t (s)	x (m)	y (m)
37.100	-4.850	-8.192
37.133	-4.850	-8.192
37.167	-4.814	-8.191
37.200	-4.731	-8.180
37.233	-4.667	-8.178
37.267	-4.577	-8.167
37.300	-4.505	-8.165
37.333	-4.437	-8.166
37.367	-4.369	-8.167
37.400	-4.301	-8.165
37.433	-4.234	-8.166
37.467	-4.157	-8.166
37.500	-4.089	-8.167
37.533	-4.047	-8.178
37.567	-3.970	-8.180
37.600	-3.894	-8.181
37.633	-3.840	-8.193
37.667	-3.791	-8.204
37.700	-3.727	-8.206
37.733	-3.702	-8.217
37.767	-3.677	-8.229
37.800	-3.648	-8.243
37.833	-3.615	-8.255
37.867	-3.563	-8.257
37.900	-3.545	-8.270
37.933	-3.525	-8.282
37.967	-3.526	-8.294
38.000	-3.519	-8.308

Fig.ii.1, time and corresponding cartesian coordinates

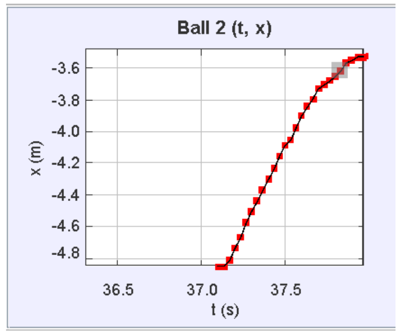
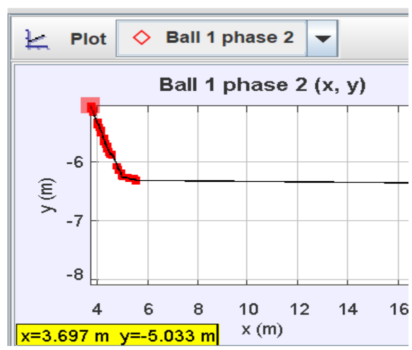


Fig.ii.2, position in the x direction vs. time

$\frac{1}{2}(5)(1.92)^2 = 9.22J$

$\frac{1}{2}(2)(2.46)^2 = 6.05J$

To calculate the coefficient of restitution, we use the following formula:



$e = -\frac{V_{2f}-V_{1f}}{V_{2i}-V_{1i}}$, where V_2 refers to the seesaw and V_1 to the green ball.

So, $e = \frac{=(2.46)}{-1.92} = 1.28$

i) Inelastic collision: pink ball and the first domino

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Fig.iii.1, velocity of green ball after coming out of the tube

Analysis of results

Energy of pink ball: $KE = \frac{1}{2}mv^2$;

Velocity of pink ball: $V_I = 0$; $V_F = 1.48\frac{m}{s}$

$$\frac{1}{2}mv_{pink\ ball}^2 = \frac{1}{2}(5)(1.48)^2 = 5.76J$$

All the kinetic energy is transferred to the first domino as the pink ball stops after the collision.

Conservation of energy: Green ball falling from the tube

Analysis of results

Tracker was not able to track inside the tube.

Height of tube: $3.8m$

Mass of green ball: $5kg$

Gravitational acceleration: $9.81m/s^2$

$$PE = mgh; PE = 5 * 9.81 * 3.8 = 186.39J$$

PE converts into KE

$$KE = \frac{1}{2}mv^2$$

Velocity of green ball: $\frac{0.73m}{s}$

$$KE = \frac{1}{2}(5)(0.73)^2 = 1.33J$$

Conservation of Momentum: Green ball hitting the vertical seesaw

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Tracker was not able to track the seesaw.

In conservation of momentum, $m_1v_1 = m_2v_2$

Key: gb= green ball, ss= vertical seesaw

$$m_{gb} = 5kg; m_{ss} = 2kg$$

$V_{i,gb} = \frac{1.92m}{s}; V_{f,gb} = 0$
$V_{i,ss} = 0; V_{f,ss} = \frac{2.46m}{s}$
*To calculate conservation of momentum:

$$p = mV_{i,gb} = (5)(1.92) = 9.6kg * \frac{m}{s}$$

$$p = mV_{f,ss} = (2)(2.46) = 4.92kg * \frac{m}{s}$$

48.75% of the momentum is lost, so the conservation is imperfect.

v) Projectile: Green ball bouncing down the staircase

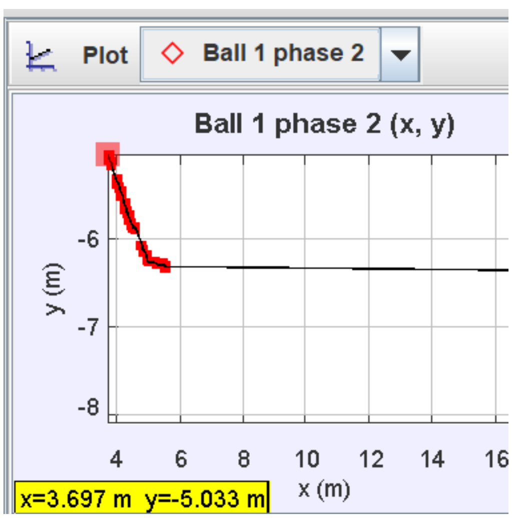

Table Ball 1 phase 2

t (s)	x (m)	y (m)
21.467	3.697	-5.033
21.500	3.697	-5.033
21.533	3.747	-5.085
21.567	3.771	-5.113
21.600	3.798	-5.138
21.633	3.824	-5.164
21.667	3.956	-5.315
21.700	3.981	-5.342
21.733	4.006	-5.368
21.767	4.006	-5.368
21.800	4.057	-5.420
21.833	4.082	-5.447
21.867	4.108	-5.473
21.900	4.133	-5.500
21.933	4.215	-5.596
21.967	4.265	-5.650
22.000	4.290	-5.677
22.033	4.315	-5.704
22.067	4.341	-5.730
22.100	4.366	-5.756
22.133	4.392	-5.782
22.167	4.391	-5.783
22.200	4.417	-5.809
22.233	4.443	-5.834
22.267	4.475	-5.855
22.300	4.490	-5.859
22.333	4.547	-5.862
22.367	4.580	-5.886
22.400	4.773	-6.078

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Fig.v.1, velocity of green ball after coming out of the tube

vi) *Fig.v.2, position in x & y vs. time for projectile ball*

vii) To find the velocity of the green ball bouncing down the staircase, we can use the graph above to find the slope of the line, which is about $\frac{0.73m}{s}$.

viii) $m_{ball} = 5kg$; Initial KE of the ball = 1.33J

ix) $KE_{ball} = KE_{initial,ball} + GPE_{ball}$

x) $KE_{ball} = 1.33 + mgh = 1.33 + (5)(9.81)(6.97) = 341.88J$

xi) In this case, KE is added to GPE since the ball is falling downwards.

xii) For horizontal velocity, we have $\Delta x = 1.08m$ and $t = 0.933s$, so $V_x = \frac{1.08}{0.933} = \frac{1.17m}{s}$

xiii) *Assuming negligible friction, there is no acceleration in the x direction

xiv) For vertical velocity, we have $\Delta y = -1.05\ and\ t = 0.933s, so\ V_y = -\frac{1.13m}{s}$

xv)

xvi) Circular motion: green ball rolling in the circular disk

Fig.vi.2, angular acceleration vs.

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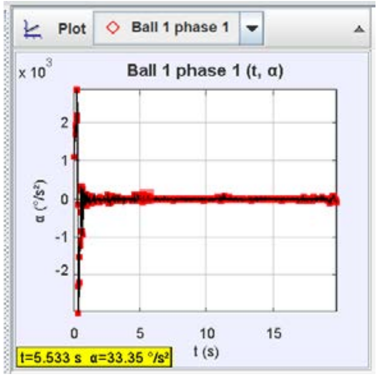
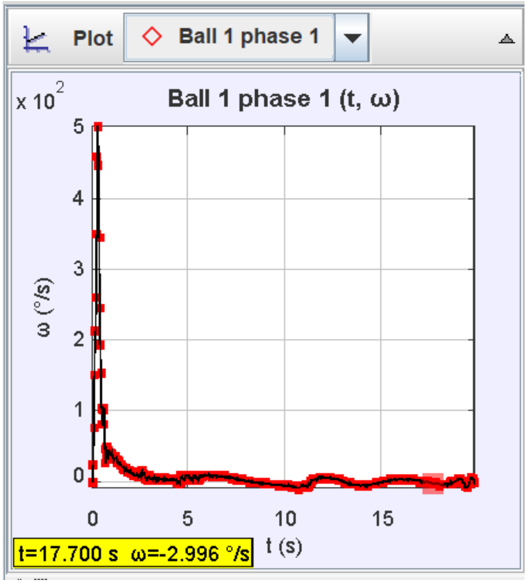


Fig.vi.1, angular velocity vs. time



The data I got from Tracker was completely unreliable as it did not track the ball accurately. Thus, I did some manual tracking. Initially, the angular velocity of the green

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ball is 0. As it speeds up, it reaches a maximum velocity of 6.56 rad/s, or 375.86 degrees/s.

For angular momentum, $L = I\omega$

The time needed for the ball to complete one rotation is 0.96s

$\omega = \frac{\Delta\theta}{\Delta t};\ \omega = \frac{2\pi}{0.96} = 6.56\frac{rad}{s}$

The radius of the ball is 0.15m; the mass of the ball is 5kg

So, $I = \frac{1}{2}(5kg)(0.15m)^2 = 0.056kg * m^2$

Then, $L = I\omega$; $L = (0.056)(6.56) = 0.37kg * \frac{m^2}{s}$

For centripetal acceleration, $a_c = \omega^2 r$

$r_{ball} = 0.15m;\ a_c = (6.56)^2(0.15) = 6.46m/s^2$

Torque: Vertical seesaw spinning

*Tracker could not track the movement of the seesaw.

After the green ball hits the seesaw, it starts spinning. Before that, the seesaw was at rest. At the moment of collision, the seesaw suddenly gains angular velocity due to the force of the ball causing a fast acceleration. When the seesaw starts moving, the average angular velocity is 1.073 rad/s. The seesaw was active for about 0.72sec before stopping again.

As we have calculated previously, $KE_{green\ ball} = 9.22J$ and $KE_{seesaw} = 6.05J$. So, 66% of the energy from the green ball is transferred to the seesaw.

The mass of the seesaw is 2kg, and the radius is 4m

$KE_{seesaw} = \frac{1}{2}I\omega^2$

$I = \frac{1}{2}(2kg)(4m)^2 = 16kg * m^2$

$\omega = \sqrt{\frac{2KE_{seesaw}}{I}} = \sqrt{(2 * 9.22)/16} = 1.073\frac{rad}{s}$

$\Delta t = 0.72s$ for the seesaw to rotate;

$$\alpha = \frac{\Delta\omega}{\Delta t} = \frac{1.073}{0.72} = 1.49\ rad/s^2$$

$$Torque = I\alpha = (16)(1.49) = 23.84\ \mathrm{N * m}$$

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Conclusion

Originally, I was going to put the dominos in the middle of the whole process, but I couldn't think of a way to crack the egg in the end. In order to meet the requirements and the constraints of the given task, I had to redesign and start over the project several times. Some of the objects I had pictured in my head were too complicated to create, and so in some case, I went online and downloaded some models to try out. Some of them made it to the end like the staircase and the curvy tunnel slide. I also adjusted the settings numerous times to ensure the machine functioned perfectly. My machine ran for about 41 seconds, which met the time requirement. I was stuck on the torque part for a long time, since it was relatively hard to construct and there were not many models online. Despite the ups and downs along the way, I ultimately built a reliable and consistent Rube Goldberg Machine.

Although the machine was a success, there were many things that could be improved on. One of them was the visibility of the movements. The machine included two tunnel-like objects, which means I could not see what was going on in them. This gave me a big headache since Tracker was not able to track an object if it cannot be seen. Thus, I had to do some manual tracking to continue carry out the calculations. In the future, if I were to build it again, I would make the outer surface of the tunnel-like objects transparent, so the movements happening inside of them can be tracked at all times. I would also design a better section to demonstrate projectile in 2-D. The current section only demonstrates a small amount.

What I learned from designing and building the machine is that everything that happened in the machine was under perfect conditions, meaning that the air resistance was negligible. If it were built in real life, the outcome would've been completely different as there are many external factors affecting the movements of the objects and therefore the calculations and outcomes would be very different.

Rube Goldberg machine is simple yet complex. Individual steps might be short and simple, but put together, they're powerful.

References

[1] Blender Beginner Tutorial, YouTube, 16 July 2020, https://youtu.be/TPrnSACiTJ4
[2] Part 2, Level 1: Modeling – Beginner Blender Tutorial Series, YouTube, 16 July 2020, https://youtu.be/RaT-uG5wgUw