Laboratory Development for Dynamic Systems Through the Use of Low Cost Materials and Toys

Dr. Benjamin Reed Campbell, Robert Morris University

Ben Campbell holds a BS in physics and MS in electrical engineering from Penn State and a PhD in engineering from Robert Morris University. For the first decade of his career, he worked as a laser engineer at the Penn State Electro-Optics Center. In 2011 he joined Robert Morris University as an Assistant Professor of Engineering. He has been supporting RMU's biomedical engineering program and also teaching dynamics, circuits, and introduction to engineering. Since 2005, Dr. Campbell has served as faculty for the Pennsylvania Governor's School for the Sciences (a summer program at Carnegie Mellon) and currently sits on the Board of Directors for the PGSS Campaign, a nonprofit that is responsible for raising the funds to finance and sustain the program.

Dr. Luis E Monterrubio, Robert Morris University

Aug 2013 - Present Assistant Professor, Mechanical Engineering Robert Morris University

June 2010-Aug 2013 Postdoctoral Fellow University of California, San Diego Structural Engineering Department

Ph.D. - Mechanical Engineering - (University of Waikato, New Zealand) M.A.Sc. - Mechanical Engineering - (University of Victoria, Canada) B.E. - Mechanical Engineering - (Universidad Nacional Autonoma de Mexico)

Dr. Tony Lee Kerzmann, Robert Morris University

Tony Kerzmann received both a Bachelor of Arts in Physics from Duquesne University and a Bachelor of Science in Mechanical Engineering from the University of Pittsburgh in 2004. After graduating, Tony Kerzmann enrolled in graduate school at the University of Pittsburgh where he graduated with a Master in Science and a Doctor of Philosophy in Mechanical Engineering, in 2007 and 2010, respectively. Currently, he is an assistant professor at Robert Morris University, where his research goals include, hybrid concentrating photovoltaic systems, energy system life cycle assessment, sustainable product development, and active learning.

Laboratory Development for Dynamic Systems Through the Use of Low Cost Materials and Toys

Abstract

In an effort to provide students with a hands-on learning experience while demonstrating dynamics concepts, the authors have developed several laboratory activities. The goal of these laboratories is to engage students in an active learning exercise that employs higher level thinking skills to integrate multiple course concepts. The laboratories are focused on inducing the analysis, synthesis and evaluation levels of Bloom's Taxonomy. Each laboratory was designed with low cost materials that are readily available at most hardware and toy stores. The labs were intentionally created to be easy to implement for undergraduate or high school physics and dynamics. Using children's toys also provides a psychological effect to make the experiments less intimidating for students struggling with dynamics concepts by adding an element of fun. All measurements for data collection can be made with a tape measure and scale. Time values are not recorded, but can be calculated and verified if precise timing equipment is available. For an added degree of complexity, students were given the optional challenge to use smart phones to record the motion of an object and use frame analysis to extract position, velocity and acceleration data. The labs explore the topics of position, velocity, acceleration, circular motion, force, momentum, elasticity, and more. The result is a simple and cost-effective set of dynamics laboratory activities which would be easy for other engineering programs to introduce into a curriculum or use for educational outreach events. One of the main advantages of the proposed laboratory activities is its portability.

Introduction

Many studies have shown that engineers are active learners and therefore hands-on experiences are an important part of their education.[1] Dynamics is a subject where creating hands-on learning laboratories in a cost effective manner can be a challenge.[2] At Robert Morris University most of the engineering courses have laboratory components. The department, however, has limited dedicated laboratory space and therefore the engineering professors have to be creative in the development of these laboratories. In order for the Dynamics professors to accommodate hands-on, experiential learning while engaging the students in an area that they enjoy, the professors decided to incorporate toys into the laboratories. In the last two years, this has proven to be a very effective way to not only easily and cheaply develop a variety of laboratories, but also create a great deal of interest in the students. Students have commented that conducting the laboratories was fun and enjoyable. The laboratories engage the students in cognitive synthesis and evaluation; the two highest levels of Bloom's Taxonomy while also strengthening their understanding of the subject matter.[3] Using toys for teaching is not novel;[4] neither is using building blocks, cars, robots, and many other games to connect concept with practice in lab[5,6,7,8,9] but those efforts are usually targeted toward youth. This work is applies toys from childhood to college level dynamics concepts to show sophistication of science in the simplicity of play.

The professors also benefit from the ease with which these laboratories can be transported. Most of the laboratories are small enough to fit in a briefcase and can be assembled or disassembled in a minimal amount of time. This not only allows for easy transport and storage, but also allows for the majority of class time to be used on the exercises themselves, rather than in the lab setup as with some laboratories that rely on complex equipment. Because toys are used in the labs, the ease and timeliness with which lab configurations can be changed has provided the opportunity for professors to cover multiple experiments in a single class period. This also allows the students to rapidly change lab configurations when trying to solve a problem.

Dynamics Course Layout

The topics covered in lecture portion of this course are based on the text book Dynamics: Analysis and Design of Systems in Motion, 2nd Edition.[10] The subjects that are covered in this course are as follows:

- Motion of translating bodies
- Inertial Response of translating bodies
- Energetics of translating bodies
- Multibody Systems
- Kinematics of rigid bodies undergoing planar motion
- Vibratory Motion

The laboratories for this course follow the in-class lecture materials and provide a way for the students to get a real-life perspective of the theory and equations that are learned in class.

Dynamics Laboratory Development

The laboratories of the Dynamics course were developed using inexpensive toys that allow observing the physical meaning of the equations given in the theoretical lectures. Laboratories were set up using toys like the Daredevil Stunt Set (Figure 1) and Hot Wheels Car Launcher with accessories (Figure 2). These toys allow launching small cars and motorcycles at different speeds. In addition it is possible to build a loop or launch the toys at different specific angles and speeds. In addition, billiard and tennis balls are also used in the laboratories. The above material allows a better understanding of problems related with position, velocity, acceleration, circular motion, force, momentum, elasticity and other topics related with the Dynamics course. These demonstrations can be simplified to fit a general physics curriculum, or can be made more challenging through deriving equations, requiring vector formats, conversion between coordinate systems, elasticity considerations in collisions, and other modifications.

Figure 1 Daredevil Dynamics Set (Motorcycle)

Figure 2 Hot Wheels variable speed launcher, ramps and loop used with standard Hot Wheels cars. Accessories can be purchased individually for approximately $5 each to get the desired components for lab activities without having to buy large, expensive sets with unwanted pieces.

Summary of Labs

1. Hot Wheels Dynamics - Set up the variable speed launcher on the edge of a table, launch cars at different speed settings off the table and measure the horizontal distance traveled to first impact with the floor. Use distance traveled and height of table to calculate the average launch speed for each launcher setting. With multiple trials, statistics can also be incorporated for calculating deviation of launch speed and other error sources.

2. Hot Wheels Launch Angle - Use a variable speed launcher and the ramp to map the equations of motion for the projectile by measuring its travel distance after launch. Calculate where to place a second ramp to catch the car during its flight. Place the ramp and test the hypothesis.

3. Daredevil Dynamics - A toy motorcycle travels around a loop and the launches off an inclined ramp. The distance traveled provides velocity at launch. Centripetal acceleration around the loop can be estimated, and the highest point of the parabola can be calculated. Students set up a miniature high jump apparatus (borrowing vertical metal rods on stands, and a couple clamps from the chemistry lab and suspending a coffee stir stick as the high jump bar between them) to a precalculated maximum height and distance from launch for parabolic peak and test if the object clears the bar.

4. Hot Wheels Force - Using various starting velocities and lengths of track leading into the loop (for deceleration) the vehicle is launched around the path. Students observe when the vehicle separates from the track surface to calculate when the centripetal force exceeds gravitational force and estimate how much deceleration is occurring from the initial launch position, to the peak of the loop.

5. Daredevil Momentum - This lab uses only a portion of the Daredevil Stunt Set. A half loop is constructed to act as a track for balls to roll down, as seen in Figures 3 and 4. Billiard balls and tennis balls are used to demonstrate momentum. By colliding different combinations of balls into each other, momentum and elasticity can be calculated. The standard Hot Wheels loop does not have as much stability as the Daredevil loop (which has a reinforcement support), and is not recommended for balls of this size and weight.

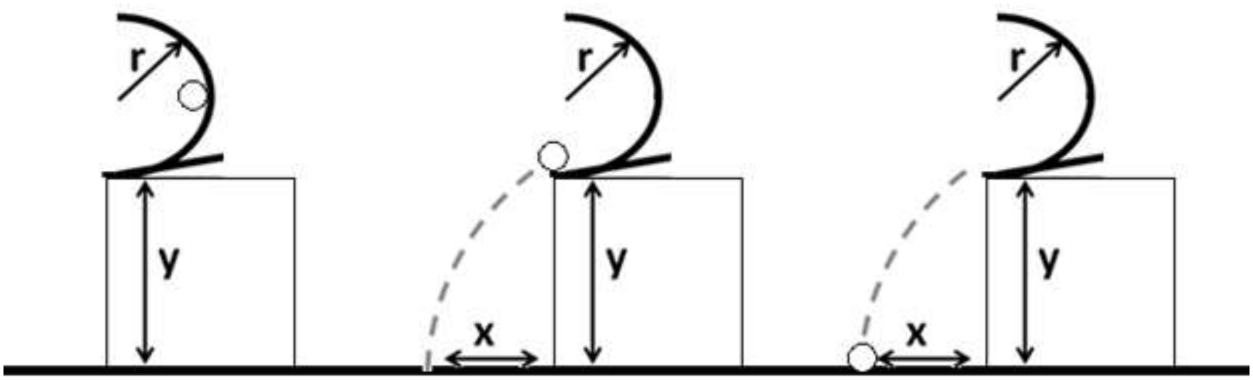

Figure 3 Single ball setup for Daredevil momentum and energy

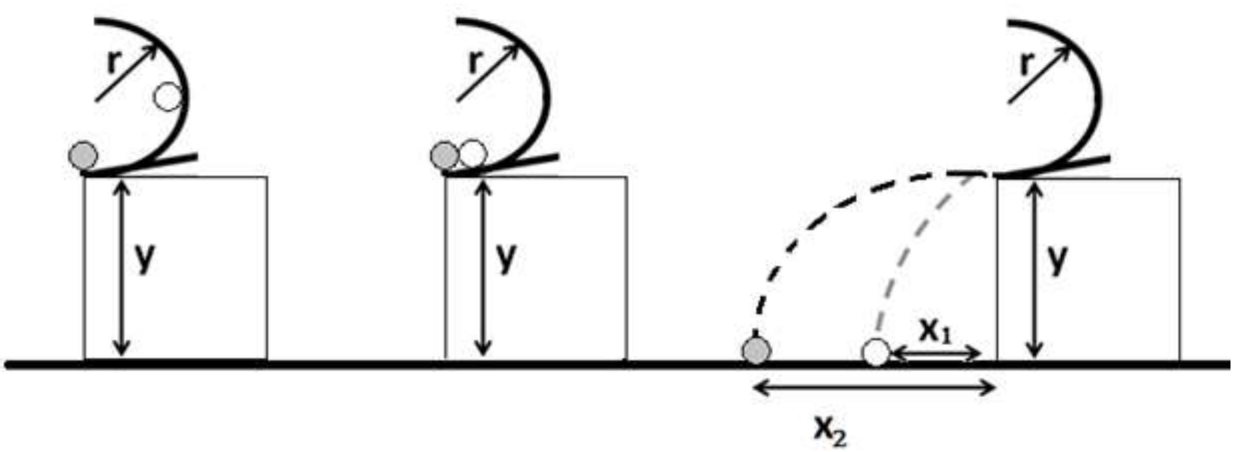

Figure 4 Two ball setup for Daredevil momentum and energy

6. Daredevil Energy - Using data from a previous lab (Daredevil Momentum), calculate the potential and kinetic energy of the ball in various locations throughout 2D space before and after collision.

7. Hot Wheels Energy - Use the data from a previous lab (Hot Wheels Dynamics) to examine the energy states of the car in motion. The lab incorporates kinetic, gravitational and spring energy and allows the student to derive an expression for as well as calculate the spring constant for the launcher.

Course Outcomes

Of the eleven ABET student outcomes for engineering programs, five outcomes (a, b, c, e & k) were expected to be satisfied by this course:[11]
a. An ability to apply knowledge of mathematics, science and engineering
b. An ability to design and conduct experiments as well as to analyze and interpret data
c. An ability to design a system, component, or process to meet desired needs
e. An ability to identify, formulate, and solve engineering problems
k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Student Feedback and Survey Results

Responses from students were obtained to assess engagement and get ideas about improving the laboratories. Students found the laboratories relevant, fun and educational. A sample of student feedback:

- "The projects greatly helped me understand the topics of dynamics better."
- "The inertia and force experiments were very helpful."
- "There could have been some sort of experiment to help understand flow rate better. That topic was somewhat hard to comprehend."
- "Not only was it fun for the students, but for the instructor I'm sure it was easy and affordable to provide."
- "The set up was very practical to the application of the theory."
- "I liked doing the labs. It was a fun way to learn the material and apply it to real life situations."
- "I feel that my knowledge and ability to solve problems grew while doing the labs."

The comments exemplify how the students felt about the labs which were apparently enjoyable and added to their comprehension. Suggestions were made to attempt to relate some of the more difficult concepts through laboratory activities, which is an excellent suggestion for future work in this area. Students have also suggested being given freedom to design their own lab activity, and the instructors have considered the possibility of offering extra credit for students who design their own lab experiment using existing or low cost resources in future classes. Students need space to conduct these labs so they spread out in the engineering building and the experiments are highly visible to other students and professors. Other faculty have commented how active and engaged the lab team are when working on these projects.

Figure 5 Students working on lab (the picture is an unsolicited addition to a lab report by the students)

The end of course survey for one of the professors from the Fall 2012 and Fall 2013 semester can be seen in Table 1 The Labs remained largely unchanged after the first offering to get a larger sample size for feedback. On a 5 point Likert scale students responded in the following manner about the labs and the course in general:

Table 1 End of course survey results, Fall 2012 (15) Fall 2013 (24).

39 responses from three course sections taught by the same professor	5	4	3	2	1	Not used	Average score
	very effective	effective	moderately effective	somewhat effective	in-effective		
Laboratory exercises for understanding important course concepts	23%	54%	15%	5%	3%	0%	3.90
Assigned projects in which students worked together	15%	44%	18%	5%	3%	15%	3.74
	Much more than most courses	More than most Courses	About the same as other course	Less than most courses	Much less than most courses	Omit or N/A	
This course helped me to think independently about the subject matter	15%	49%	33%	5%	3%	0%	3.85
This Course actively involved me in what I was learning	13%	38%	46%	3%	0%	0%	3.62
I studied and put effort into the course	21%	44%	36%	0%	0%	0%	3.85
I was challenged by this course	26%	46%	28%	0%	0%	0%	3.97

The survey response echo's the student comments, with 77% of students finding the labs to be effective or very effective to help understand course concepts. When the question was rephrased in terms of working with other students (teamwork), only 59% gave it top scores of 4 or 5, but the fall in score can be attributed mainly to 15 present responding that students did not work together during the course. It was observed that some groups did take a "divide and conquer" approach by rotating lab responsibility or let the most competent person do all the lab work, which was not the intended approach for the activity. On these types of team the lab activity itself may have been looked on more favorably than the teamwork aspect. In comparison to other courses at Robert Morris University, a majority of the students found the course overall helped them to think independently about the subject matter (64%) and were actively involved in the learning process (51%) more than other courses. A majority of students thought the course was also more challenging (72%) and required more effort (65%) than their other courses. The comparisons to the other courses are in reference to the entire dynamics course, not just the labs. Because the course is perceived as difficult, the labs involving toys are intended to make the content relatable to an activity which is perceived as simple. The scores show that effort needs to be made in active engagement and emphasizing share participation and teamwork in the lab activities. Lab groups should be kept small to allow everyone to be hands on. Due to availability of lab materials group sizes ranged from 2-5 students, and from observation three or less group members appeared to be optimal so that each person was hands-on and contributing.

Conclusions

The experience setting up laboratories with toys has been very successful. Students have been able to carry out the labs that have helped to further clarify engineering concepts related with Dynamics. In addition, the laboratories were inexpensive and there was no need for specially designated rooms or installed equipment. The students enjoyed learning while receiving hands on experience gave the students a real-world perspective on the subjects that they learned in class. There was no need for stop watches, timing gates, distance sensors, video capture or any other timing equipment although these instruments could provide a valuable addition to expand the data collection capabilities during the lab sessions. In this initial trial of the lab setups it was convenient for the students and professors to keep the labs simple by not using any sophisticated measurement equipment. This not only kept the cost and complexity of the setups to a minimal level, but also allowed the students to focus on the course material that was tied to each lab. In addition to the ease of setup and minimal purchase costs, these labs take up very little storage space and are easily reproducible by simply purchasing the Hot Wheels toy sets and a tape measure.

The Hot Wheels toys do have limitations with relation to the course content. Topics such as multi-bodied systems, rigid body motion, variable mass, and vibration, have not been addressed using these lab materials. It may not be possible to demonstrate these topics well using the Hot Wheels sets alone. Additional equipment would be necessary to comprehensively teach these more sophisticated topics. There are certainly more ways in which these toys could be applied to teaching dynamics and can also serve as an outreach tool to demonstrate dynamics concepts to middle and high school students.

References

1. Dunn, R., & Carbo, M. (1981). *Modalities: An Open Letter to Walter Barbem Michael Milone and Raymond Swassing*. Educational Leadership, p. 381-382.

2. Butterfield, R. (1997), Benefit Without Cost in a Mechanics Laboratory. Journal of Engineering Education, **86**: 315–320. doi: 10.1002/j.2168-9830.1997.tb00304.x.

3. Bloom, B. S., & Krathwohl, D. R. (1956). *Taxonomy of Educational Objectives*. Handbook I: The Cognitive Domain. New York, NY, U.S.A., David McKay Co. Inc.

4. J Güémez *et al* (2009) Toys in physics lectures and demonstrations—a brief review *Phys. Educ.* **44** 53

5. Featonby, D. (2005) Toys and Physics. *Phys. Educ.* **40** 537.

6. Wagner, G (2009) A Circular Motion Activity with Hot Wheels® Rev-Ups Phys. Teach. **47**, 11.

7. Wang, E. L., LaCombe, J., & Rogers, C. (2004). Using LEGO® Bricks to Conduct Engineering Experiments. In Proceedings of the ASEE Annual conference and exhibition.

8. McNamara, S., Cyr, M., Rogers, C., & Bratzel, B. (1999). LEGO brick sculptures and robotics in education. In ASEE Proc.

9. Jolley, W. O., Rencis, J. J., Cobb, E. C., & Hagglund, R. R. (2002). Incorporating a LEGO® fourbar mechanism project in undergraduate dynamics. In Frontiers in Education, 2002. 32nd Annual (Vol. 3, pp. S4D-16).

10. Tongue, B. H., (2010). Dynamics: Analysis and Design of Systems in Motion, 2nd Edition. John Wiley & Sons.

11. ABET (2014) *Criteria for Accrediting Engineering Programs, 2014-2015*, http://www.abet.org/eac-criteria-2014-2015/. Accessed 1/4/14.

Appendix 1: Example Laboratory, Lab 1

Hot Wheels Dynamics

Lab 1: Determining Initial Velocity through Projectile Motion

Introduction

In this lab we encourage you to play with toys! You are going to assemble the Hot Wheels Launcher shown above. The orange Hot Wheels car launcher (Not to be confused with the Daredevil Stunt set's yellow motorcycle launcher) is a variable speed launch system with four settings. This makes it ideal for experiments to see the effects of velocity on projectile motion. You are then going to launch a car with various initial velocities and measure how far it lands. From the launch distance and height data, you can calculate the motorcycle's initial velocity.

Items needed:

Measuring Tape
Hot Wheels Orange Car launcher
One toy car

Setup

1. Find a desktop or tabletop area with plenty of open space straight ahead (tables or workbenches in learning factory work well)
2. Place launcher at edge of elevated surface with front of launcher lined up with the edge of the table. It is ok if the launcher's tongue extends beyond the table edge.
3. Measure the vertical height to the launch point and record it
4. Then extend the tape measure along the ground
5. Pull back the spring loaded launcher to the desired position
6. Place the car in the launcher (make sure it is centered).
7. Push the button to release the car

Insert Picture of your setup here:

Experiment

First measure the height of the launcher off the floor.

Launch Height H **: ________________ inches**

Measure the amount of spring extension

The Hot Wheels multi-speed launcher has a rubber band that can be stretched to store spring (potential) energy used to launch the vehicle. Release the launch button so the rubber band is not stretched. Use the front of the launch sled for your position measurements. Pull back the launch sled to the first speed setting. Measure the elongation "e" of the band (distance that the front of the sled moved). Repeat this for the other three sled position setting.

Launch Position	1	2	3	4
	in	in	in	in
Elongation e				

Record the horizontal distances traveled for each launch position

Place the launcher on a table top and align the front of the launcher with the edge of the table (the tongue of the launcher will overhang the edge). Launch the toy car five times using each launch position and calculate the average distance for each set up.

Launch Position	Distance d 1	Distance d 2	Distance d 3	Distance d 4	Distance d 5	Average Distance
	in	in	in	in	in	in
1						
2						
3						
4						

Determining Time of Flight

Show a derivation of an equation to determine the "time of flight" t in terms of the height of the car at launch position and gravity (which is equal to the acceleration of the car in the vertical direction).

Launch Position	Time airborne t
	s
1	
2	
3	
4	

Determine the launch velocity

Show a derivation of a formula to solve for horizontal initial velocity $\underline{v_0}$ in the $\hat{\imath}$ as a function of launch height, horizontal flight distance and gravity. Use the average distance traveled to calculate the average initial velocity at launch for each of the positions

Launch Position	Average initial velocity $v_0\ \hat{\imath}$
	in/s
1	
2	
3	
4	

Determine Landing velocity

Show first the derivation of an equation for the final velocity v_f in the vertical ĵ direction and assume that the velocity in the horizontal direction is constant. Then calculate the total magnitude of the landing velocity adding the horizontal and vertical velocity components.

Launch Position	$v_f \hat{\imath} = v_0 \hat{\imath}$	$v_f \hat{\imath}$	$\lvert v_f \rvert$	$\lvert v_f \rvert$	$\lvert v_f \rvert$
	in/s	in/s	in/s	ft/s	m/s
1					
2					
3					
4					

Questions to solve and answer in lab report (to be done later once all data is collected).

1. What assumptions did you need to make in your calculations?
2. What effect does the mass of the car have on the experiment? If you had a heavier toy car, what would be the effect on the experiment and why? Would anything change?

Please write general comments about the lab.

Appendix 2: Example Laboratory, Lab 7

Hot Wheels Energy

Lab 7: Work, Kinetic Energy, Potential Energy and Spring Stiffness

Introduction

In this lab you will use the data collected in lab 1 “Determining Initial Velocity through Projectile Motion” to calculate the work done to compress the elastic band of the launcher, the stiffness coefficient of the elastic band as well as the potential and kinetic energy of the car from the launching position till it reaches the ground.

Read Lab 1 with your answers to remember the procedure you used to solve for the initial and final velocities of the toy car.

Equations

The relevant equations for this lab covered in class are

- Work done is proportional to the change in kinetic energy *KE*

$$W_{1-2} = KE_2 - KE_2 = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$$

The equation above states that the work W_{1-2} done from state 1 to state 2 is equal to the change in kinetic energy, where m is the mass of the particle and v_2 and v_1 are the velocities of the particle at states 1 and 2.

- Work on a spring

$$W_{1-2} = \int_{s_1}^{s_2} F_t\, ds = \int_{x_1}^{x_2} kx\, dx = \frac{1}{2}k\left(x_2^2 - x_1^2\right)$$

Where k is the stiffness of the translational spring that can be defined in lbs/in, while x is the elongation or compression of the spring. W_{1-2} is also equal to the potential energy *PE* stored in the spring.

- Potential Energy due to gravity

$$PE_g = mgy$$

Where g is the acceleration due to gravity and y is the height of the particle with respect to a “zero” reference.

- Conservation of energy

$KE_2 + PE_2 = KE_1 + PE_1 + W_{1-2}$

Recalling data from lab 1

In Lab 1 you used the Hot Wheels multi-speed launcher that has a rubber band that can be stretched to store spring (potential) energy, which you used to launch a toy car. Recall the measurements with the spring extension of the four possible set ups of the launcher together with the launch height, average horizontal distance traveled by the car and the initial and final velocities of the car.

Launch Position	Spring elongation e	Launch height H	Average horizontal distance d	Initial velocity v_0	Final velocity v_f
	in	in	in	in/s	in/s
1					
2					
3					
4					

Calculate the stiffness of the spring for each launch position. **Show a sample calculation**

Calculate the work on the spring for each launch position. **Show a sample calculation**

Launch Position	Work on spring W	Spring stiffness k	Spring elongation e
	in	lbs/in	in
1			
2			
3			
4			

Develop an equation to calculate the kinetic energy and potential energies at different times/locations of the car in the horizontal direction. Plot your results

In a second plot suppose that the car falls with an initial velocity equal to zero. Calculate the kinetic and potential energy at different times (from the start of the free fall to the time when the car reaches the floor). Then plot the results for the kinetic energy, the potential energy and the total energy. Total energy is equal to the kinetic energy plus the potential energy.

Please write general comments about the lab.