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Studio Section 008 – Eric Johlin
Team 5
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Final Report: The Great Moment of Inertia Race

Design Project B

Aradhya Bansal, Matthew Choi, Samin Akhand, Jacek Jan Wyszowski, Saket Bedi

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1 Introduction and Background

The goal of this project was to support the learning of the moment of inertia at a grade 12 high school level using an intuitive yet thorough instructional device incorporating mechanical, electrical, and software engineering principles in the design process. The moment of inertia is a fundamental physics concept that is usually neglected at this stage due to its perceived complexity—it is expected that using the device will make the concept more accessible and intuitive to the students.

The moment of inertia is an objects innate **resistance to rolling** and is the primary factor in determining how much of an objects potential energy is converted into rotational kinetic energy—it can be thought of as the analog to mass in linear motion, but in rotational motion. The greater the moment of inertia, the more potential energy is converted to rotational kinetic energy, and, as a result, the less is converted to translational kinetic energy. The moment of inertia is defined with respect to a specific rotation axis [1]; this means that a single object can exhibit different values for the moment of inertia, all dependent on which axis it is rotated about.

What makes the moment of inertia so interesting and unique is that an objects moment of inertia is solely dependent on the **geometry** of the object, or, the distribution of mass along the center axis of the object – completely independent of weight, or size.

The moment of inertia of a point mass can be derived as follows [1]:

$$\tau = Fr$$

$$\tau = mar$$

$$\alpha = \frac{a}{r} \therefore \ \tau = mr^2\alpha$$

$$mr^2 = I \text{ (Moment of Inertia)} \rightarrow \tau = I\alpha$$

Simple geometrically shaped objects like spheres and cylinders have pre-determined moments of inertia that are derived with calculus, as can be seen in Figure 9 from the Appendix. This means that for simple shapes, the shape geometry that has the lower moment of inertia will **always** win a downhill rolling race. See Appendix for moments of inertias of simple shapes.

The device itself is designed to allow students to discover the concept of rotational kinetic energy, and therefore, the moment of inertia, through calculations and through general qualitative observation. As a high-level overview, the device is simply a ramp with 4 pairs of infrared sensors, one at the top and three at the bottom (one in each of three lanes), connected to and programmed with a raspberry pi

(Linux machine). These IR sensors have been programmed to output the time it takes for three objects rolling down the ramp at once (one in each of three lanes) to travel the distance of the ramp. From the time, and other values the students can measure during the lab, like mass, initial height, and distance travelled, the students will be able to determine a value for the objects rotational kinetic energy by calculating the difference between the objects starting gravitational potential energy and translational kinetic energy.

Students will find that there is a correlation between the computed rotational kinetic energy and the time it takes the object to roll down the ramp. The higher the rotational kinetic energy, the longer it should take the object to roll down because it means less potential energy was converted to translational kinetic energy, which is directly proportional to the velocity of the rolling object. Through general observation, students will also be introduced to the concept of the moment of inertia--after the lab, they will be shown a table with the formulas for the moments of inertias of the objects they were rolling down the ramp (hollow cylinder, solid cylinder, solid sphere) and they should find that the objects that have a lower moment of inertia will have always "won" the race down the ramp, no matter the size of the object. This will show students that the moment of inertia is a purely geometric property--students should be able to come to the conclusion that the moment of inertia is proportional to the distribution of mass around an objects axis of rotation.

This report includes a detailed summary of the teams goals and constraints coming into this project, and a thorough set of instructions that will allow anybody to build the device the team built following core engineering design principles. In addition, included is also other deliverables of the project, including instructions on how to use the completed device and a lesson plan for teachers and students.

2 Problem Definition and Problem Specifications

2.1 Problem Definition

Needs of the Students:

A grade 12 student for whom the instructional aid to be developed is intended for requires of the device that it be simple yet thorough in its delivery of the theory behind a scientific concept, intuitive and analogous with the concept itself, and robust in its handling. Students need clear instruction so they don't get confused while using the device and require a demonstration of the potential risks and mitigations that may be associated with the handling of the device--safety of the students should be a priority.

Needs of the Instructors:

Instructors who will be using the instructional aid to teach their students will require of the device that it come with a ready-made lesson plan that can be followed through and completed in a single class of approximately 1 hour, clear learning outcomes so the teacher's own lesson associated with the device itself can be planned accordingly, and all the necessary equipment bundled together for easy accessibility and some degree of portability. Instructors also require the device to be safe to use with and around younger students and the potential dangers, if any, with using the device should be made very clear so the instructor can take the proper precautions.

High-Level Project Goal

In the first-semester of physics of most STEM university programs, a very broad range of concepts is covered in a very short period of time; for concepts like the moment of inertia and rotational kinetic energy, time is required to be able to process and truly understand the concept, however, at the current stage, most students go into the semester lacking a foundational knowledge of the concepts to truly grasp them by the time the exam comes around. With such a core physics concept like the moment of inertia which has wide spread applications in many industries, the team has recognized a need for an introduction to the concept at an earlier stage in a students STEM career. By introducing this in grade 12, it helps professors better teach this in university as the foundations are already built and thus more time can be spent flushing out the concept and making students as comfortable as possible over the first semester of physics. Further highlighting the importance of this concept is its widespread use and application in engineering; examples include wheels and tires, combustion engines, and even pole vaulting. With such a core topic, there just is not enough time to newly teach it in a crammed first year course, therefore, the specific outcome expected of this device is that it be used to introduce the moment of inertia and rotational kinetic energy to students interested in STEM careers at the grade 12 level, making the first semester of university easier for both the students and their professors.

2.2 Problem Specifications

Learning Outcomes (LOs)

By the end of a lab associated with the instructional device, successful students would be able to:

1) explain what intrinsic properties of an object affect its ability to roll down an incline.
2) identify by only visual analysis which between two simply shaped objects has a greater moment of inertia.
3) identify and explain the existence and necessity of rotational kinetic energy as an analogous to translational kinetic energy.

Design Objectives

1. **Safety (Primary)** - To not compromise with the safety of the client is a primary objective of the design team. While all risks will be minimized, all potential risks and mitigations must be made very clear in an instruction sheet given to the instructor to make sure all proper precautions are made. It would be disastrous if anybody got injured at school during a lab and the team was held responsible, therefore, safety must be the number one priority.
2. **Portability (Primary)** - A primary objective of the team is to make sure that the instructional device and all of its components are portable and small enough to be moved around a classroom, and from one classroom to another within a school by the instructor and if needed some student volunteers. Multiple classrooms would likely be using the instructional device within a single school; easy transportation will make an instructors job much easier.
3. **Ease of Use (Primary)** - The concept being taught by the instructional device must be intuitive and the lesson plan should be easy to follow by both the instructor and students. The moment of inertia is a seemingly complex topic and current labs are not very easy to use, making understanding the concept that much harder, so the device must resolve this issue.
4. **Accessibility (Primary)** - The instructional device should be accessible to as many students as possible at a single time in order to maximize the efficiency of the device in teaching students

within the duration of a single lesson. Instructors have limited time to run a lesson so it is essential that all the students be able to use the device individually or in small groups to complete their labs within the lesson time.

5. **Learning Challenges (Secondary)** - The device might be handled by somebody with a learning disability (deaf, blind, etc.) but the concept should still be delivered just as coherently to them as somebody without a learning disability. Many classrooms have disabled learners who would be unable to benefit from a lab if it wasn't accessible to those with disabilities.
6. **Language Barrier (Secondary)** - Ideally, there would be no language barrier in using the device and anybody who speaks any language would be able to understand the concept being taught. The number of students in Canadian High Schools for whom English is their second language is increasing steadily and it is imperative to future growth that education is made more accessible to these learners.

Design Constraints

1. **Cost** - The device will be made from components that do no cost the team more than a total of $400. The services taken from the university will not cost more than $100. Materials that are scavenged and/or borrowed will not add up to a total value of greater than $200. Given this constraint, almost all individual components used in the device must be sustainable and cost effective.
2. **Size** - The device must fit within a footprint of 50 cm x 50 cm and be no higher than 100 cm tall, therefore, it must utilize individual components that aren't bigger than the sum of what their whole should be.
3. **Mass** - The instructional device cannot weigh more than 15 kg, therefore, chosen materials should take into account the material's strength-to-weight ratio and materials with higher ratios should be chosen over materials with lower ratios.
4. **Efficiency** - The instructional device should be able to sustain a minimum of at least 3 students using it to collect data at a single time. The rate at which students complete the lab should be approximately 5 students / 10 minutes to allow 30 students to complete a lab in a 1 hour time period--suitable for a typical high school class lesson. To accomplish this, multiple "lanes" or duplicates of certain components will be created so multiple students can utilize the instructional device at the same time.

5. **Time** - The device must be completed well before the actual design showcase to allow ample time for testing and modifications. The device will be finished by February 28th, giving the team approximately 2 weeks to make necessary modifications to ensure optimal functioning of the device by the date of the showcase.

3 Final Design

3.1 Overall Design

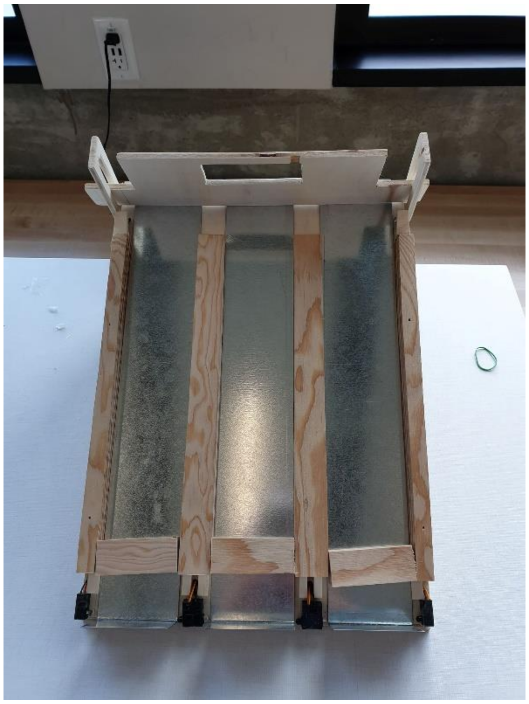


Figure 1: Top View of Completed Device

A top view picture of the completed device can be seen in Figure 1. The device enables three simply shaped objects, specifically solid spheres, solid cylinders, and hollow cylinders, to be raced against one another at once to introduce the concept of rotational kinetic energy and the moment of inertia. Nine different objects of the three varieties specified above, but of varying radii were all machined out of carbon steel by the University Machining Services—these object can be seen in Figure 10 from the Appendix. The frame of the device is constructed completely from plywood, chosen for its durability, low cost, and light weight; the frame is the shape of a hollow right triangular prism and built upon a foundational plywood base with a hole in the back to allow access to all electrical components.

As can be seen in Figure 11 in the Appendix, housed inside the frame is a raspberry pi connected to a breadboard that holds all the wiring that allows software to interact with four pairs of infrared sensors located at the top surface of the device. These infrared sensors track motion to start and stop a timer in each of three lanes based on when an object passes through them, one at the top and three at the bottom of the ramp, one in each lane.

As can be seen in Figure 12 in the Appendix, at the top, there is a wooden lane blocker with two posts on the side to ensure that it is kept straight; this “blocker” has a built in handle that allows a user to pull it up and allow whatever objects are placed at the top of the ramp to begin rolling down at the same time—the top IR sensors are positioned after this barrier to start the timer as soon as the objects begin to roll. As seen in Figure 13 from the Appendix, each of the three lanes has a metal sheet hot glued over it to reduce the friction between the rolling objects and the surface they are to roll on. These metal sheets were made slightly longer than the ramp itself and curved at the edge to serve as a barrier the objects won’t pass when they complete the race; the metal sheets also ensure that the coefficient of friction is consistent amongst the three lanes. In the same figure, it can also be seen that the three lanes are separated by plywood barriers to ensure rolling objects stay in their own lane. As seen in Figure 1, at the bottom of each of the lane are small plywood blocks that are loosely wedged in-between the barriers of each lane—these blocks are meant to get hit by each object to be pushed forward and cover the infrared sensors in each lane completely. This ensures consistency amongst trials given that the blocks are set up the same in-between each trial or any distance measurement are remade for every trial.

The final mass of the device was 8 kg and the final dimensions were 40x30x17 cm, making the device fall well within the outlined physical constraints.

3.2 Design Documentation

In line with one of the team’s primary objectives, the components of the device can be categorized into three main disciplines; electrical, mechanical, and software components. As such, the components that fall under each of these disciplines will be detailed below.

3.2.1 Mechanical Components

All the mechanical components of the device serve to ensure the proper physical functioning of the device. In implementing the mechanical aspect of the device, the team had to ensure that the overall size of the device fit within the specified constraint of 50x50x50 cm and the weight of the device did not exceed fifteen kilograms as specified (to stay in line with the portability objective), the cost of materials did not exceed $400, and that there were no imminent safety risks associated with how the materials were used; for example, all wood or metal used had to be sanded and smoothed as much as possible to ensure there were no rough or sharp edges that could injure a student or teacher handling the device.

<u>Rolling Objects</u>

Before beginning the construction of the actual device, the team had to ensure they had the objects that they would be rolling down the ramp of the device; having these objects before beginning construction would allow the team to conduct appropriate testing to make design decisions while constructing the device. While the team tried to find suitable objects online, the best option came out to be getting the objects custom machined at the University Machining Services workshop out of carbon steel at Western University. The machining itself was provided for free and the team only had to pay for materials. As can be seen in Figure 14 of the Appendix, the cost of the carbon steel objects was only $10.00—as seen in Figure 10, the dimensions of the objects are relatively small, and this is because the larger the objects, the greater the costs would have been. In the interest of cost the team though that settling for the diameters of 1”, 0.75”, and 0.5” would be fine.

<u>Foundation for Frame</u>

Instead of preliminarily deciding all the dimensions of the device, the team decided it would be best to work within the given constraints and let the final dimensions of the frame come out in the work the team did in building the device; the logic behind this was that the team would make the best decisions for the size based on qualitative observation and really considering what would be feasible for a student or teacher to handle; at the end of the day, a student or teacher won’t care what the specific dimensions of the device are as long as they can safely handle it, therefore, the team considered this the most effective and simple approach to go about building the device.

The team started with a foundational plank of plywood to serve as the base of the device; the dimensions of this plank were 40 cm in length, 30 cm in width, and 2 cm in depth (40x30x2 cm). On top of this base, two triangular blocks were attached using two 2” screws on each block, in line with the edges that were 40 cm in length. These screws were screwed in approximately 5 cm along both edges of the triangular block along the 40 cm length. These triangular blocks were 2 cm wide and had a height of 17 cm, making the angle of inclination approximately 23 degrees and the length of the hypotenuse approximately 43 cm, as can be seen below in Figure 2.

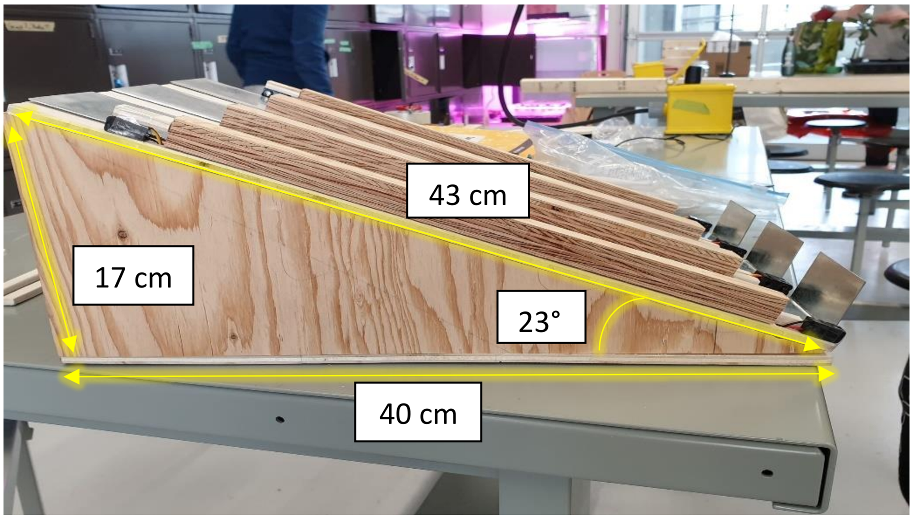


Figure 2: Construction of Triangular Blocks

The team came to the conclusion of using these dimensions after trying to roll the machined objects down a ramp from various heights and oriented at multiple angles of inclinations. The team observed what angle of inclination and height allowed the device to remain within the design constraints but also allowed which object was winning the race to be clearly seen, a crucial aspect of the laboratory component to go along with the device. After multiple trials in a range of heights of 10 cm – 20 cm, and angles of inclination between 15 and 30 degrees, the team found that a height of 17 cm and angle of inclination of 23 degrees appeared to be the best option.

The Ramp

On top of these triangular blocks of plywood, a second plank of plywood that was 43x30x2 cm was placed. Three lanes were created on top of this surface by placing four plywood barriers, the two middle ones being 2.5 cm wide and the two outer edge ones being 2 cm wide, evenly spaced out by 7 cm, the preferred width of each lane. This width was chosen for the lanes because when the objects were rolled down the ramp in the center of some area, it was found that their horizontal drift never exceeded 3.5 cm, making a total width of 7 cm suitable. Three sheets of metal were cut out and hot glued onto the ramp surface to cover each measured lane as seen in Figure 13 of the Appendix, however, the sheet metal lanes were made longer than 43 cm; they were made 47 cm in length, giving the team the ability to curve them upwards and have a blocking barrier at the bottom of the ramp that was 4 cm high—this dimension was chosen because it is more than enough to completely cover the diameter of the largest object which is 1” (2.54 cm).

Side Barriers and Holes

The barriers that were made of plywood were made 32 cm in length and placed 4 cm up from the bottom of ramp surface that in total was 43 cm in length; the barriers were attached using hot glue. This was done because the team knew that infrared sensors, each approximately 3 cm in length, would need to be placed at the bottom of the ramp below the barriers. In addition, space for holes that would need to be drilled on the ramp had to be made; given these requirements, the team chose 4 cm up from the bottom as a suitable distance. Four holes a quarter inch in diameter were drilled 3.5 cm up from the bottom of the ramp using a drill; these holes were positioned directly underneath the four side barriers on the ramp and were drilled to allow the wires on the infrared sensors to go into the frame to connect to the breadboard. The details of the infrared sensors will be touched upon in the electrical components section.

The ramp piece with the glued on barriers was finally attached to the frame of the device using a high-pressure nail gun and four nails, two on each of the barriers on the edge of the ramp. The positions of these nails are highlighted in Figure 3 below.

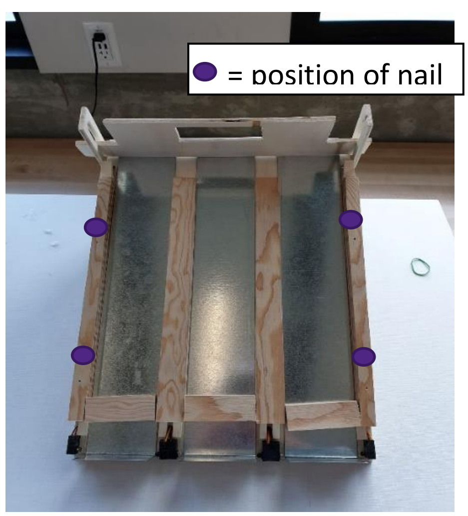


Figure 3: Location of Nails on Ramp

<u>Start Barrier with Handle</u>

At the top of the ramp, the team developed a thin plywood barrier with a handle that fits in two thin slots attached to the sides of the device using hot glue. This barrier completely blocks any objects from going down the ramp until the barrier is pulled up using the handle that is also cut into the barrier itself. The barrier is in total 34.1 cm in length and 9 cm in height, shown in Figure 4 and can be pulled up so the bottom of the barrier is 4 cm above the surface of the ramp as seen in Figure 5, allowing the widest object of 1” in diameter to easily start moving down the ramp. As seen in Figure 5, the slots are positioned right before where the infrared sensors at the top of the ramp are positioned, allowing the beam to be broken as soon as the objects start rolling.

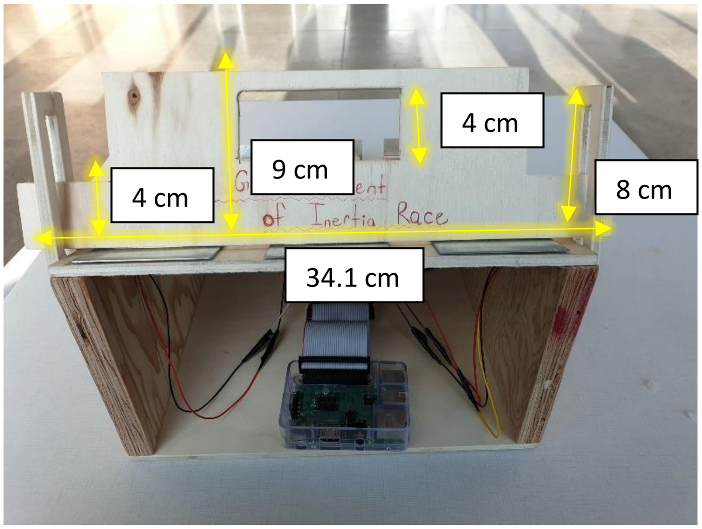


Figure 4: Construction of Race Barrier

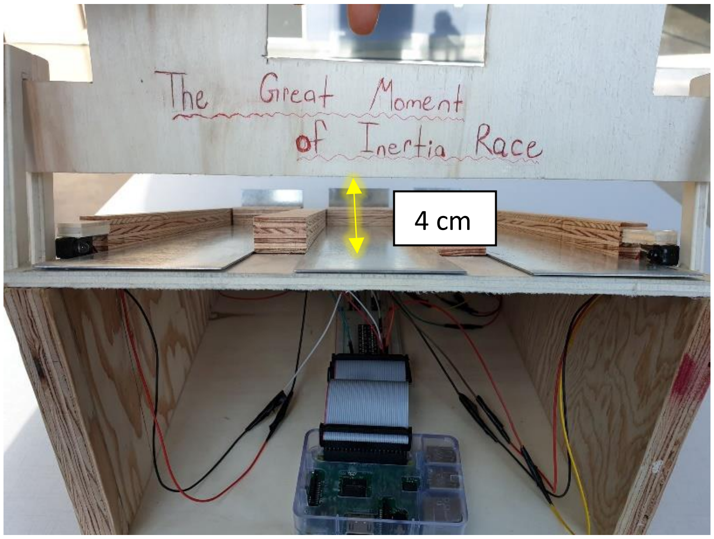


Figure 5: Race Barrier when Raised

3.2.2 Electrical Components

The electrical components of the device were comprised of a raspberry pi that the team already owned, a breadboard to connect wires too, wire extenders, a GPIO (General Purpose Input/Output) breakout pin with a ribbon cable to connect the raspberry pi to the breadboard, and four pairs of infrared sensors, each with a transmitter and a receiver. As seen in Figure 14 of the Appendix, the total cost of the electrical components seems somewhat costly at the surface, however, considering that the raspberry pi was already owned, the total cost then drops by $89.99, making the team's plan to use electrical components as sophisticated as these that much more reasonable; especially when considering that a raspberry pi has the full capabilities and even more versatility than a lot of PCs and laptops!

The circuitry attached to the breadboard is shown in Figure 6. All the wires, including the infrared sensors themselves, had to have wire extenders attached to them using electrical tape. These wire extenders not only made the wires longer, but also made the connections on the breadboard more secure as seen in Figure 7, ensuring that the connection would not fall apart if the device were to be carried around.

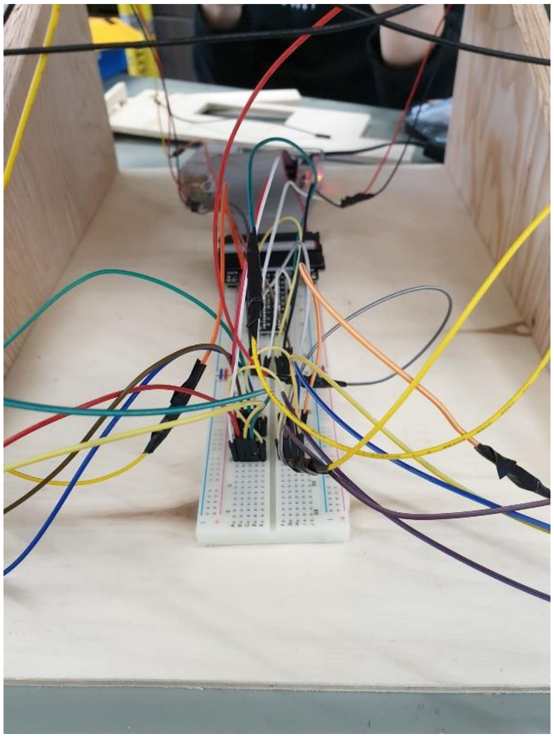


Figure 6: Wiring on Breadboard

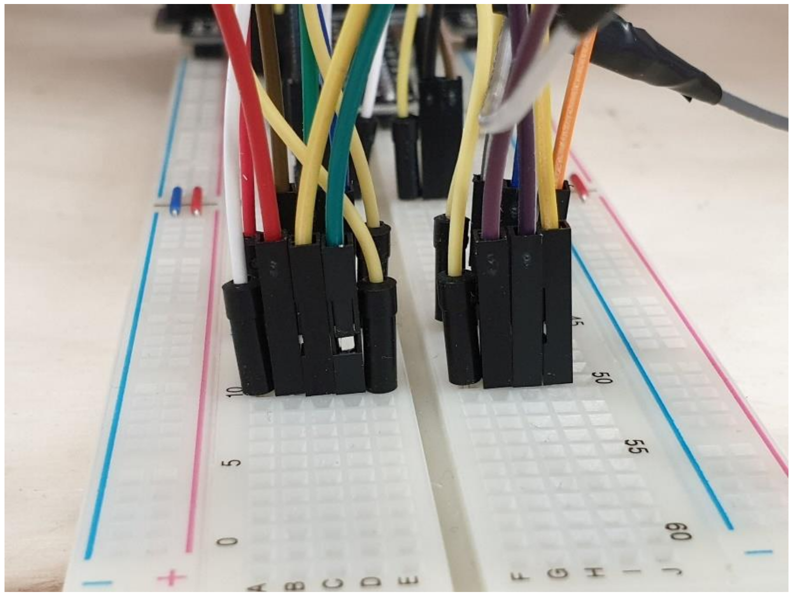


Figure 7: Secure Breadboard Connections

How the raspberry pi connects to the breadboard and interacts with the infrared sensors through its software is using something called general purpose input/output pins. These are a set of digital pins on the raspberry pi that if certain electrical components are attached to, can be accessed through software on the raspberry pi. A ribbon cable is used in tandem with something called a GPIO breakout pin to transfer all the digital pins on the raspberry pi onto a large breadboard so there is more space to play around with. Each infrared sensor is made up of a pair of components, a transmitter and a receiver; the transmitter has two wires, a ground and a 3.3 V power wire, while the receiver has three wires, a ground, a 3.3 V power wire, and a third wire called a digital input wire that connects to one of the GPIO pins on the raspberry pi to allow the raspberry pi to collect data from the infrared sensor. The circuit shown in Figure 6 connected each wire of the infrared sensor to the appropriate hole in the breadboard and the result was the messy looking circuit seen. The team decided this way okay because all the circuitry would be hidden inside the frame of the device and therefore did not need to look very appealing.

The infrared sensors were all placed onto the ramp surface with a little bit of hot glue and scotch tape to hold them in place; the top sensors also had a cover of plywood on top of them to keep them in place. The wires of the infrared sensors, technically the wires of eight components in total with each having a transmitter and a receiver, were passed through the holes that were drilled through the ramp in accordance with the mechanical specifications of the device—the wires passed through the holes were attached to the proper position on the breadboard; black wires were connected to ground, red wires were connected a 3.3 V power, and yellow wires were connected to a digital input pin.

To power the raspberry pi, it had to be either plugged into a power bank or an outlet. In addition, to interact with the raspberry pi it had to be connected to an external HDMI monitor, a wired keyboard, and a wired mouse. However, the team found an alternative to this that allowed them to use the raspberry pi on their own laptops, with the laptop acting as the monitor, keyboard, and mouse all-in-one! This is unconventional and it is expected that in an actual classroom setting teachers would connect the raspberry pi device to a smart board projector and a keyboard and mouse that is usually lying around in every classroom, however, for the purpose of developing the project, being able to interact with the raspberry pi on a laptop was much more convenient. The reason this is so unconventional is because the raspberry pi is essentially a whole computer in of itself, just like a laptop, and therefore the team had to use a virtual machine on one of the group member's laptops to simulate the desktop of the raspberry pi on the laptop itself—this involved using a cloud server that both the raspberry pi and laptop were connected to and spoke with. When it was all working, the only thing that needed to be plugged into the raspberry pi was as power source, either a power bank or into an outlet, which made the teams objective of portability that much more feasible to accomplish.

3.2.3 Software Components

For the device to function properly and for students to be able to use the device effectively to conduct a lab, an original program had to be developed on the raspberry pi that interacted with the infrared sensors. This program was chosen by the team to be written in python because python is a high level language and was already installed on the raspberry pi. The software specifications of the program were this:

1) When the first infrared beam is broken at the top of the ramp, start a timer in all three lanes
2) When an object finishes the race and lands at the bottom of the ramp, stop the timer for that lane and record the time
3) Repeat step 2 until all objects have completed the race
4) Display the time it took each object to travel down the ramp on the screen in a visually appealing GUI (Graphical User Interface)

The development of the software involved the use of various python libraries including Circuit Python to interact with hardware connected to GPIO pins of the raspberry pi as well as Tkinter, a library that allows users to develop a graphical user interface, which is essentially just a new window that appears on the screen that displays data in accordance with the specifications of the software. The logic used in the code involved the extensive use of loops and Boolean logic, as can be seen in Figure 15, 16, and 17; these figures include the exact code used by the raspberry pi to achieve the software specifications outlined earlier. How a student would interact with the raspberry pi and the software is detailed in Figure 18 of the Appendix that actually shows the exact experimental procedure a student would be provided with in a real laboratory setting. A screenshot of what the developed GUI looks like and how it displays the results of the race can be seen in Figure 19 from the Appendix.

4 Lesson Plans and Usage

To review, the learning outcomes of students who complete a lab associated with the device are as follow: By the end of a lab associated with the instructional device, successful students would be able to:

1) explain what intrinsic properties of an object affect its ability to roll down an incline.
2) identify by only visual analysis which between two simply shaped objects has a greater moment of inertia.
3) identify and explain the existence and necessity of rotational kinetic energy as an analogous to translational kinetic energy.

The students should be provided with background information of the subject being taught in the lab, a materials list, a list of variables in the experiment, and a thorough risk assessment, all of which are detailed in Figure 20 of the Appendix. The students should follow the lab procedure detailed in Figure 18 of the Appendix exactly and record their data in tables that they must design, emphasizing the importance of other lab skills that students have developed by grade 12, the target grade of the device. The data the students should record include:

- the distance the object travels
- the mass of each object
- the starting height of the object
- the time it takes the object to complete the race (outputted by device)
- which shapes wins in each race

From the data the students collect from the lab, it is expected that they will follow the following order of logic to achieve the 3rd learning outcome, which is to explain the existence and necessity of rotational kinetic energy.

1) With the distance and time, the students should be able to compute the average translational velocity of the object
2) Knowing the mass of the object and the starting height, students should be able to compute the initial gravitational potential energy of the object
3) Knowing the mass and the computed average velocity of the object, students should be able to compute the average translational kinetic energy of the device, a concept and formula they should be familiar with by grade 12 physics
4) Already having seen the conservation of energy by grade 12, students should compare the computed translational kinetic energy with the computed gravitational potential energy; unless they already knew about rotational kinetic energy, students should be surprised to see that all the potential energy was not converted into translational kinetic energy
5) The students should compute the difference between the gravitational potential energy and translational kinetic energy, and they will then be left with a number that they will soon realize is their computed value for the average rotational kinetic energy of the object they rolled down the ramp

Following this train of logic, which they should be guided through by the teacher who should have a thorough understanding of the topic already, students should then be asked questions that are detailed in Figure 21 of the Appendix to assess and develop their understanding of the topic. The questions themselves will include important information that will ensure the solidification and assessment of the first two learning outcomes identified for this lab. Questions 10 and 11 in Figure 21 of the Appendix specifically address the first two learning outcomes; if students are able to answer those two, and the rest of the questions, all eleven of them, then it can be concluded that the student has achieved all three of the specified learning outcomes of the lab and have develo9ped a foundational understanding of rotational kinetic energy and the moment of inertia.

5 Design Decisions

Throughout the project, there were many iterations and changes to the original idea. The changes from first prototype to final product are best demonstrated by actually seeing what the teams first prototype looked like, which is seen below in Figure 8.

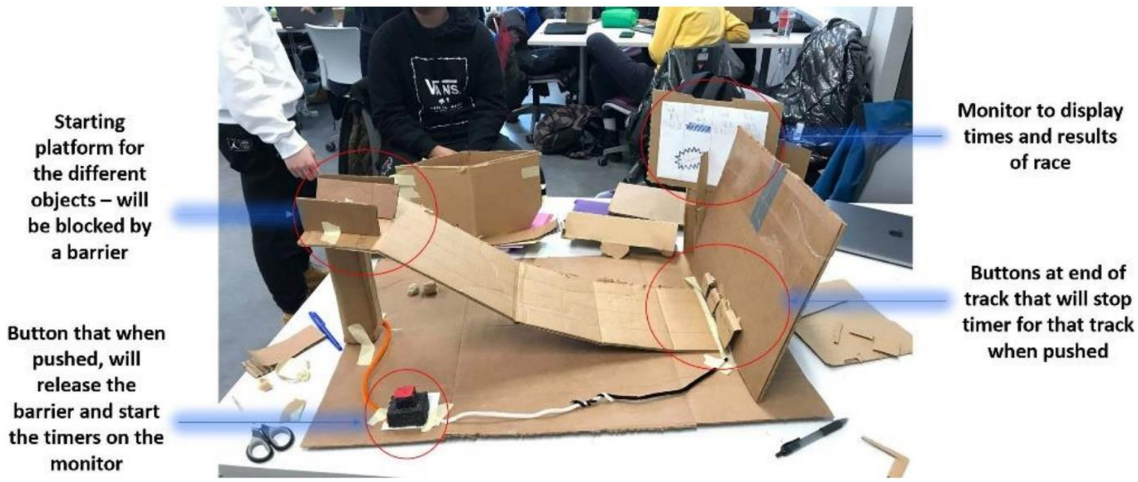


Figure 8: First Design Prototype

The original prototype included one large start button that would start both the timer on the monitor being controlled by the raspberry pi and also activate a motor that would lift a barrier at the top of the ramp that would allow the object to start rolling down. In addition, at the bottom of the ramp, instead of infrared sensors were buttons that would have to be pushed by the rolling objects to stop the timer in their respective lanes.

Every aspect of the device that was outlined to be implemented in the first prototype was not actually implemented in the final device for good reason in correlation with the project objectives and constraints that were presented in Section 2. There were many other design decisions that had to be made, but two of the biggest ones that had a great impact on the progress of the project are detailed below.

<u>Buttons</u>

While using buttons to both start and stop the timer would have been interesting to implement, the team realized doing so would take much more time than needed as it was easy enough to just use infrared sensors to replace the buttons at the bottom of the ramp and a digital “restart program” button, coded onto the raspberry pi, to replace the starting button. In addition, the buttons at the bottom would likely not have been activated by the smaller objects the team decided to go with, and bigger objects that would have activated the buttons would have cost more, going against one of the outlined design constraints to keep the object under a budget. The trade-off the team made here by going with the infrared sensors was losing some of the tangible and interactive components of the device, because the button was something physical the students could have pushed, however, the benefit to what the team went with is that it helped them remain more in line with their cost constraint and allowed them to meet their objective of completing the project well before the design showcase.

Motor

The team planned to use a motorized barrier at the top of the ramp because they thought it would be really fun to learn how to implement, but realized that the costs and time associated with doing so may not be worth it. In addition, using a motorized barrier as opposed to a manual one in this case would likely reduce the efficiency of the device, going against one of the team's primary project objectives. The trade-off made with going with the manual plywood barrier was that it removed a component that the team could have benefitted from learning how to use at a later point in their careers, but saved the team a lot of time, money, and made the device ultimately more efficient because a motorized barrier would have been limited by the speed of the motor.

6 Conclusion and Future Work

The purpose of this project was to design a device and associated lab to explain the moment of inertia to students at a grade 12 level. It's important for students to understand this concept given it's relative complexity but utter importance in understanding more complex concepts in STEM fields like engineering. The main objectives the team set out to accomplish in the design of this device were as follows:

1. **Safety (Primary)**
2. **Portability (Primary)**
3. **Ease of Use (Primary)**
4. **Accessibility (Primary)**
5. **Learning Challenges (Secondary)**
6. **Language Barrier (Secondary)**

The main design constraints were:

1. **Cost**
2. **Size**
3. **Mass**
4. **Efficiency**
5. **Time**

Summary of Project Outcomes

The total cost of the device was $233.37, as seen in Figure 14, the total mass was 8 kg, and the total footprint was 40x30x17 cm, making the device fall well within the cost, size, and mass constraints. In terms of efficiency and accessibility, the team sought to ensure that at least three students be able to use the device to collect data at a single time, and given that the team developed a device with three different lanes, three students actually do have the ability to use the device and collect data from it all at once. The team test collected data from the device and found that three team members could collect five different data sets after just five minutes, making an average of three total data sets per minute collected from the device—this statistic shows that the team was able to deliver an outcome that far exceeded their initial expectations.

Safety was considered one of the top priorities of the device's outcomes. A thorough risk assessment is included in the handout that would be given to each student if they were to participate in the lab; the risk assessment concludes that the device is safe and the only possible risk is the choking hazard of the smaller objects to young children, however, since the target is grade 12 students, young children should never be exposed to the objects, meaning the team achieved this objective as well!

In terms of portability, the device was well within the provided physical constraints and the best measure of the portability of the device turned out to be whether or not one person could carry the device and all of its required components. Given that one team member could easily carry the device around and from building to building, the team is confident that a teacher would be able to do the same in a school meaning the team achieved this objective.

For ease of use and understanding, the team is confident that the thorough lesson plan and guiding questions they've developed provide students with a strong foundation in the concepts of rotational kinetic energy and the moment of inertia. In fact, the created lesson plan was actually presented to a high school student to see if the could follow along and use the device, and their response was an enthusiastic yes, and they were able to sufficiently collect data and go on to answer most of the provided question all by themselves, proving that the developed product is intuitive as easy to use.

The only objectives the team was unable to hit were the secondary objectives of making the device accessible to those with learning disabilities and to those who don't speak English. Making the device accessible to those with disabilities would have required much more consideration and effort on the team's part, and given the time constraint and objective the team set out for themselves, it was difficult for them to take this into consideration when there were already so many components to the core what was to be delivered. For the language barrier objective, the team could have tried to use more images in their deliverables, like the guiding questions and experimental procedure, however, words would nonetheless have to be used to some extent and therefore the team deemed it almost impossible to make the device fully accessible to those who don't speak English unless they directly translated all deliverables that were written in English to the native language of the student.

Recommendations for Future Design Improvements

Building the device was a great learning opportunity for the team; depending on their interests, members got the opportunity to learn how to program in a new coding language, learn how to use the raspberry pi, or learn how to use new wood and metal working machines in the workshop. That being said, there are some things the team could improve upon were they to design this device again from scratch:

1. The team should try and construct the whole device and software using an Arduino instead of a raspberry pi—Arduinos are much cheaper than raspberry pi's and given that there was no extensive software development in this project, an Arduino is more than powerful enough to accomplish the required tasks.
2. Although the team thought it best to come up with specific dimensions of the device as they constructed it, it would likely be beneficial to specify these dimensions from the beginning and even make CAD models of the device to ensure that the construction process is as smooth as possible.
3. When learning something new, the team tended to shy away from the help that was offered by the University; for example, a team member spent more time than needed learning how to code something that was of no use to the team instead of simply asking somebody for help, so it is

recommended that in the future, team members be more aware of the help that is available to them.

4. It would be interesting to see if students could conduct this lab using objects that weren't simple shapes, perhaps like a pencil or other everyday objects. If rules around using these objects were included in the lesson plan, students might find the whole lab more engaging and get more from the experience.
5. While using plywood for the entire mechanical construction of the device was cheap, it would be beneficial to next time use a slightly more expensive, but sturdier wood than plywood—this would increase the durability of the device and also make it more aesthetically pleasing, making it more engaging for students

Practical, Deployable, and Sustainable

Practically, since no student would be allowed to toy with the software of the raspberry pi, there's really no benefit to including such a powerful computer on the device. That being said, if the team were able to develop the same device using the cheaper Arduino, it would make selling the device more practical. Apart from that, given the physical attributes of the device and how effective it is in teaching the concept, the team still believes that it is a practical solution to teaching the moment of inertia at a high school level.

The device is very deployable; this is because although there is a large quantitative portion to the lab, a large part of it is also purely qualitative and seeing what objects win races down the ramp and coming to conclusions about why. Given that the lab can be effective even without all the electrical and software components, it makes the device that much more deployable, but even as is, most schoolboards especially in Ontario require classrooms to have large projectors that can act as monitors and practically every school has a wired keyboard and mouse that could be used to connect to the raspberry pi.

The device is sustainable because of its ease of use and how simple it is to build; if somebody is given the code for the software that has to be developed to control the infrared sensors, then building the device is purely a matter of connecting the wires to the breadboard and constructing the plywood frame using hot glue and a nail gun. It is not very complicated and the team is confident that this design process is sustainable enough to be used for many years to come if anybody in the future decides to attempt to rebuild this device.

7 References

[1] “Moment of Inertia.” [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/mi.html. [Accessed: 1-April-2019]

8 Appendices

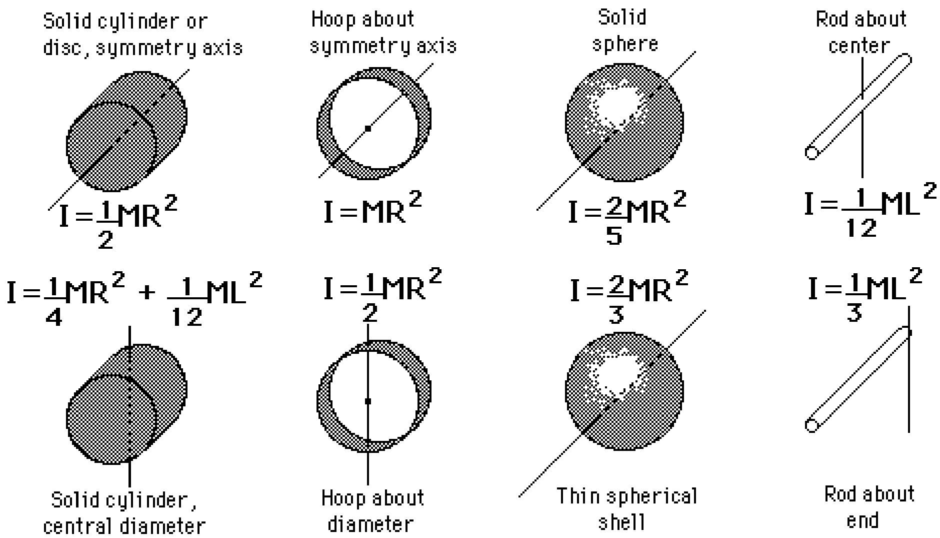


Figure 9: Moment's of Inertias of Simple Shapes [1]

Figure 10: Objects Machined by UMS

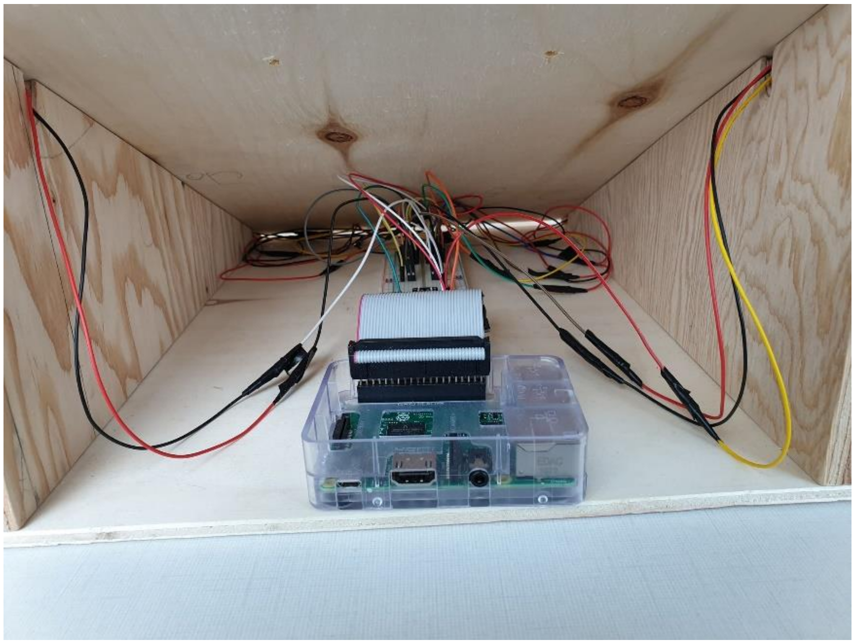


Figure 11: Electrical Components Housed Inside Device

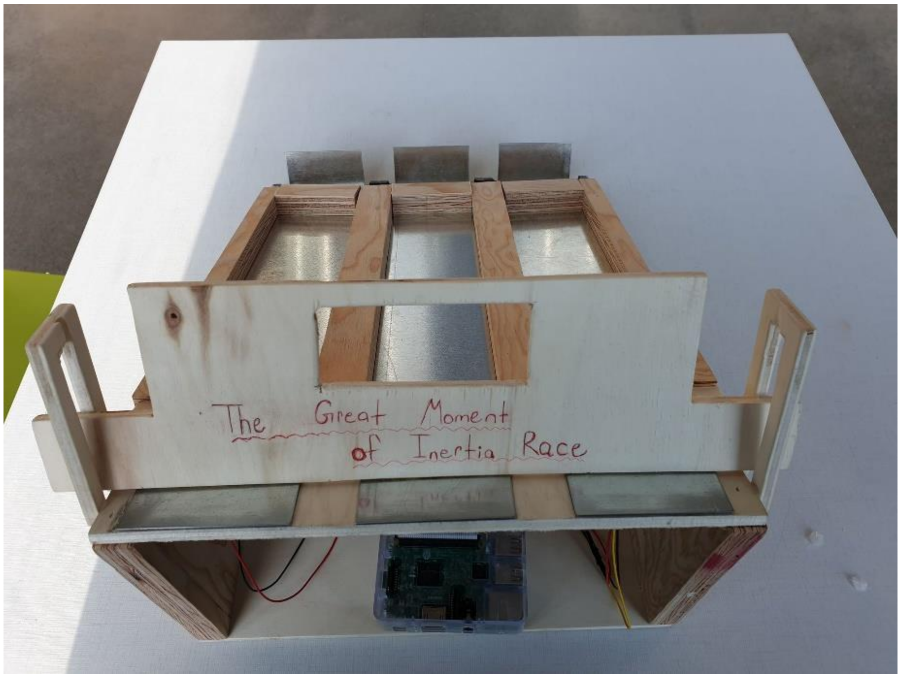


Figure 12: Top-Down View of Device

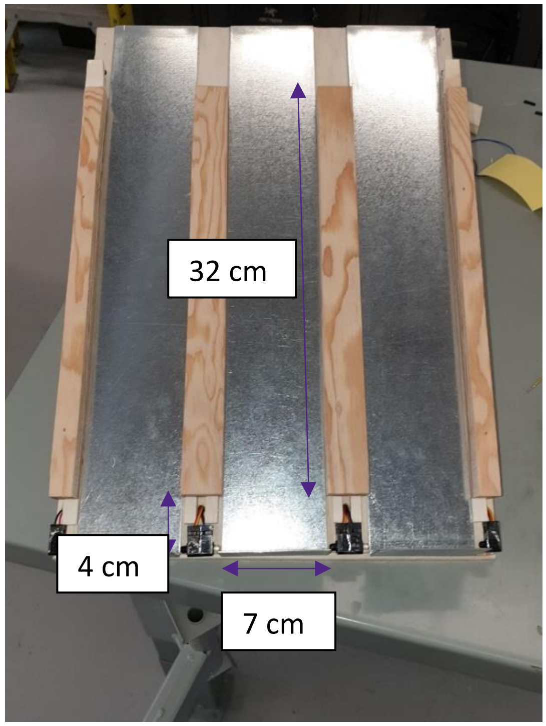


Figure 13: Metal Plates and Barriers on Ramp

Materials and Costs	
Mechanical Components	
Material	Cost
4 x Plywood Planks	$53.76
1 x Metal Sheet	$4.00
2" Screws	$4.69
Carbon Steel Objects	$10.00
SUM OF MECHANICAL COSTS	$72.45
Electrical Components	
Material	Cost
Raspberry Pi (Owned)	$89.99
Wire Extenders	$11.95
4 x IR Circuit Sensors	$45.99
1 x Long Breadboard	$8.00
1 x GPIO Breakout and Ribbon Cable	$4.99
SUM OF ELECTRICAL COSTS	$160.92
Total Cost	$233.37

Figure 14: Materials and Costs of Materials

```python
import datetime
import sys
import os
from tkinter import *
from tkinter import ttk
import board
import digitalio

break_beam1 = digitalio.DigitalInOut(board.D4)
break_beam1.direction = digitalio.Direction.INPUT
break_beam1.pull = digitalio.Pull.UP

break_beam2 = digitalio.DigitalInOut(board.D18)
break_beam2.direction = digitalio.Direction.INPUT
break_beam2.pull = digitalio.Pull.UP

break_beam3 = digitalio.DigitalInOut(board.D26)
break_beam3.direction = digitalio.Direction.INPUT
break_beam3.pull = digitalio.Pull.UP

break_beam4 = digitalio.DigitalInOut(board.D23)
break_beam4.direction = digitalio.Direction.INPUT
break_beam4.pull = digitalio.Pull.UP

while break_beam4.value == True:
    if break_beam4.value == False:
        break

start = datetime.datetime.now()

beam1 = break_beam1.value
beam2 = break_beam2.value
beam3 = break_beam3.value

lane1Running = True
lane2Running = True
lane3Running = True

while beam1 == True or beam2 == True or beam3 == True:

  if break_beam1.value == False:
      beam2 = break_beam2.value
      beam3 = break_beam3.value
```

Figure 15: First Section of Python Code

```python

  if break_beam2.value == False:
      beam1 = break_beam1.value
      beam3 = break_beam3.value

  if break_beam3.value == False:
      beam1 = break_beam1.value
      beam2 = break_beam2.value


  if break_beam1.value == False or break_beam2.value == False or break_beam3.value == False:

    if break_beam1.value == False and lane1Running == True:
        beam1 = False
        lane1 = datetime.datetime.now()
        lane1Running = False

    if break_beam2.value == False and lane2Running == True:
        beam2 = False
        lane2 = datetime.datetime.now()
        lane2Running = False

    if break_beam3.value == False and lane3Running == True:
        beam3 = False
        lane3 = datetime.datetime.now()
        lane3Running = False

print("Here are the final results of the race:")
lane1Time = (lane1 - start).total_seconds()
lane2Time = (lane2 - start).total_seconds()
lane3Time = (lane3 - start).total_seconds()

def restart_program():
    python = sys.executable
    os.execl(python, python, * sys.argv)

```

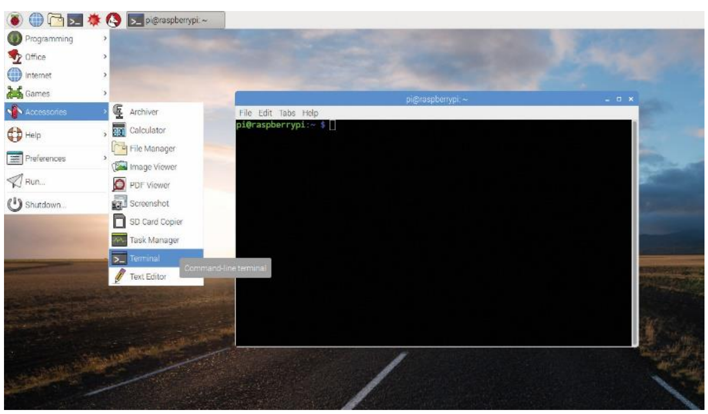
Figure 16: Second Section of Python Code

```python
root = Tk()
root.configure(background='black')
w = 800 # width for the Tk root
h = 250 # height for the Tk root

# get screen width and height
ws = root.winfo_screenwidth() # width of the screen
hs = root.winfo_screenheight() # height of the screen

# calculate x and y coordinates for the Tk root window
x = (ws/2) - (w/2)
y = (hs/2) - (h/2)

# set the dimensions of the screen
# and where it is placed
root.geometry('%dx%d+%d+%d' % (w, h, x, y))
label1 = Label(root, text="Thank you for participating in the Great Moment of Inertia Race!", background = 'black', foreground = 'white', font=("Courier", 18), wraplength = 700)
label1.pack()
label2 = Label(root, text="Here are the final results:", background = 'black', foreground = 'white', font=("Courier", 16), wraplength = 700)
label2.pack()
label3 = Label(root, text=("Lane 1 time is",lane1Time,"seconds"), background = 'green', foreground = 'white', font=("Courier", 14), wraplength = 600)
label3.pack()
label4 = Label(root, text=("Lane 2 time is",lane2Time,"seconds"), background = 'green', foreground = 'white', font=("Courier", 14), wraplength = 600)
label4.pack()
label5 = Label(root, text=("Lane 3 time is",lane3Time,"seconds"), background = 'green', foreground = 'white', font=("Courier", 14), wraplength = 600)
label5.pack()
label6 = Label(root, text="To restart the race, click the button below, or, close this window to end the program!", font=("Courier", 12),
               foreground = 'white', background = 'black', wraplength = 700)
label6.pack()
restartButton = Button(root, text="Restart Race", font=("Courier", 12), command=restart_program).pack()
root.mainloop() # starts the mainloop
```

Figure 17: Third Section of Python Code

Experimental Procedure

1. Plug keyboard, mouse, and external monitor (using HDMI chord) into the back of the raspberry pi housed within the device. A Smart Board projector will work fine as the external monitor.
2. Plug the power cable into the raspberry pi and into a nearby outlet to turn the pi on.
3. Wait for the raspberry pi to boot and reach the home screen desktop.
4. Open the terminal on the raspberry pi.



How to access the raspberry pi terminal

5. Precisely type “python3 DPB.py” into the terminal but do not press enter yet. This is the command that will start the program on the raspberry pi.

6. Measure the distance between the IR sensor at the top of the ramp and the top of one of the wooden blocks pushed against the metal at the bottom of the ramp and record the measurement.
7. Set the three wooden blocks at the bottom of the ramp in place so that the bottom of each wooden block is aligned with the bottom of the barricades on the sides of each lanes

Proper Alignment of Wooden Blocks at the Bottom of the Ramp

8. Students should weigh each of the nine objects with the digital weighing scale and record the masses.
9. Pick three of the nine objects and place each in different lanes at the top of the ramp, blocked by the hurdle so as they do not roll down yet.
10. Students should measure the vertical height from the surface the device is on to each object at the top of the ramp and record their findings.
11. Press enter on the keyboard to begin the program. If an error is received, try again and make sure “python3 DPB.py” is typed in exactly.
12. Grab the handle on the hurdle and lift up in a smooth and consistent motion and observe the objects as they all roll down the incline.
13. At the end of the race, students should record the time’s for each lane that are displayed on the monitor.
14. Click “Restart Race” on the monitor to begin a new trial and repeat steps 9-14 to collect as many data sets as desired.
15. When finished, close the terminal and unplug all wires from the raspberry pi to power it off. Clean up and store away the device and all of its components.

Figure 18: Experimental Procedure for Lab

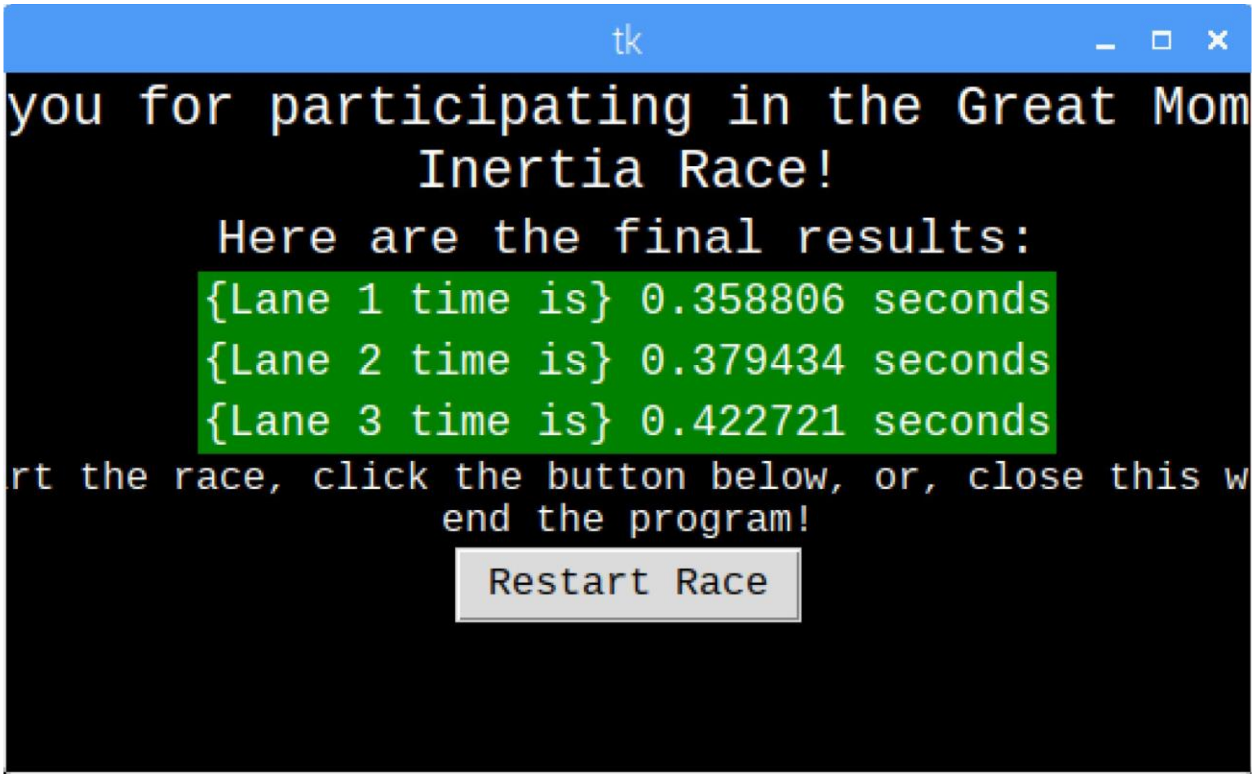


Figure 19: Python GUI Developed for Device

<u>The Great Moment of Inertia Race: A Study into the Tendency of an Object to Transform Potential Energy into Rotational Kinetic Energy</u>

1. Introduction

The moment of inertia and rotational kinetic energy are fundamental physics concepts that are usually neglected in high school, particularly in grade 12 when students actually have the necessary background knowledge to understand the concepts, due to their perceived complexity; it is expected that by the end of this lab, students will have a thorough understanding of rotational kinetic energy and how it is affected by an object's moment of inertia. The following are the expected learning outcomes of this lab and will be assessed in the assignment that follows:

<u>Learning Outcomes (LOs)</u>

By the end of the lab, successful students will be able to:

1) explain what intrinsic properties of an object affect its ability to roll down an incline.
2) understand the difference between translational and rotational kinetic energy.

3) identify and explain the existence and necessity of rotational kinetic energy as an analogous to translational kinetic energy.

2. Background Information

The moment of inertia is an objects innate **resistance to rolling** and is the primary factor in determining how much of an objects potential energy is converted into rotational kinetic energy—it can be thought of as the analog to mass in linear motion, but in rotational motion. The greater the moment of inertia, the more potential energy is converted to rotational kinetic energy, and, as a result, the less is converted to translational kinetic energy. The moment of inertia is defined with respect to a specific rotation axis; this means that a single object can exhibit different values for the moment of inertia, all dependent on which axis it is rotated about.

What makes the moment of inertia so interesting and unique is that an objects moment of inertia is solely dependent on the **geometry** of the object, or, the distribution of mass along the center axis of the object – completely independent of weight, or size.

The moment of inertia of a point mass can be derived as follows:

$$\tau = Fr$$

$$\tau = mar$$

$$\alpha = \frac{a}{r} \therefore \tau = mr^2\alpha$$

$$mr^2 = I \text{ (Moment of Inertia)} \rightarrow \tau = I\alpha$$

Rotational inertia is an incredibly important concept that comes up in any scenario involving a rotating mass; however, the most important application of the moment of inertia is likely its use in calculating the angular momentum of a object that allows us to explain how rotational motion changes when the distribution of mass changes. It is imperative to the success of tomorrow’s engineers that they have at least a solid foundational understanding of the moment of inertia, especially those who choose to pursue the mechanical stream.

3. Methodology

Variables

Independent Variable	*Object Rolling Down Incline:* Students should have the freedom to choose whichever one out of the nine provided objects to roll down the incline and to compete in the "Great Moment of Inertia Race". They can conduct as many trials as they would like, recording in each data set the shape of the object they used (solid sphere, solid cylinder, or hollow cylinder), the radius of that object, and the time it took the object to roll down the incline.
Dependent Variable	*Time Taken to Roll Down Ramp:* Depending on the object a student rolls down the ramp, the time taken to reach the bottom will be different. Students should record this time taken after each conducted trial.

Controlled Variable	Method of Control	Possible Effect on Results
Distance Travelled	The distance between the IR sensor break beam at the top of the ramp and any of the three break beams at the bottom of the ramp are all separated by the same distance within reasonable experimental bounds.	Since students will be using the distance and time to compute an average translational velocity, the distance won't actually have an effect on their computation, however, different distances would take away from any qualitative observations the students would be able to make because if each object travelled different distances, then it wouldn't really be a race.
Density of Objects	All objects have been machined and are made using the same material, carbon steel.	If the densities of the objects were different, they would have disproportionate masses that, although they shouldn't, may have slightly affected the outcomes of the race.
Coefficient of Friction	All lanes are made of steel and all objects are also made of the same material.	If the coefficient of friction between the objects and their respective lanes differed, then it would be difficult to justify that friction can be considered negligible in

		this experiment because the potential energy lost to friction is dependent on the coefficient of friction.

Materials

- 1 x “ The Great Moment of Inertia Race” ramp apparatus (provided)
- 1 x wired keyboard
- 1 x wired mouse
- 1 x external monitor and HDMI chord
- 1 x set of nine objects (provided)
- 1 x ruler
- 1 x measuring tape
- 1 x digital weighing scale
- 1 x Raspberry Pi Power Cable (provided)

Risk Assessment

- Small objects provided may be choking hazards—do not swallow
- Be careful when lifting the device, it is fragile and can break if dropped
- Do not bring water near the device, it houses electrical components on the inside

Although the device houses electrical components, none are strong enough to physically shock an individual. As long as a student is mature and can exhibit caution when handling the device, it is safe to conduct this experiment without any extra safety precautions. If students wish, they **may wear safety goggles**, but it is not a requirement.

Figure 20: Handout Given to every Student

The Great Moment of Inertia Race Assessment Questions

SA = Short Answer, MC = Multiple Choice

Q (SA) 1. What is the average translational kinetic energy of one of the objects you rolled down the ramp?

A. This number will vary from student-to-student depending on the data they collected.

Q (SA) 2. What is the gravitational potential energy of the same object you rolled down the ramp?

Q. This number will vary from student-to-student depending on the data they collected.

Q (MC) 3. Why doesn't the gravitational potential energy equal the translational kinetic energy?

A. The difference in energy is all lost to friction

B. The difference in energy is all lost due to air resistance

C. The conservation of energy is not always true

D. Some of the potential energy is converted into something called rotational kinetic energy

A. D

Q (MC) 4. True or false, the formula for rotational kinetic energy is the exact same as translational kinetic energy.

A. True

B. False

A. B

Q (MC) 5. Which of the three objects tended to win the race most often?

A. Solid Sphere

B. Solid Cylinder

C. Hollow Cylinder

A. A

Q (MC) 6. True or false, the radius of the object did not matter in the outcome of the race. The only thing that mattered was what shape the object was.

A. True

B. False

A. A

Q (SA) 7. What is different between the three different shapes with respect to their masses and distribution of the mass about the object's axis of rotation?

A. For some objects, more mass is distributed further away from the axis of rotation, while for others, more mass is distributed closer to the axis of rotation. For example, more mass is distributed away from the axis of rotation for the hollow cylinder than is for the solid cylinder.

Q (SA) 8. What is the correlation between the distribution of mass about the object's axis of rotation and which objects tended to win the race the most?

A. The object that had more mass distributed further away from its axis of rotation tended to lose more races. The hollow cylinder lost almost every race, unless it was racing another hollow cylinder.

Q (MC) 9. What is the name for the physical quantity that is a measure of the distribution of an objects mass about its axis of rotation?

A. Moment of Inertia

B. Moment of Area

C. Moment

D. Moment of Length

A. A

Q (MC) 10. True or false, the greater an object's moment of inertia, the more resistance it has to rolling.

A. True

B. False

A. A

Q (SA) 11. From the provided objects, which probably has the greatest moment of inertia and why?

A. The object that has the highest moment of inertia is the hollow cylinder because the majority of its mass is distributed much further from its axis of rotation as compared to the solid sphere and solid cylinder.

Figure 21: Assessment Questions to Ask at the End of Lab