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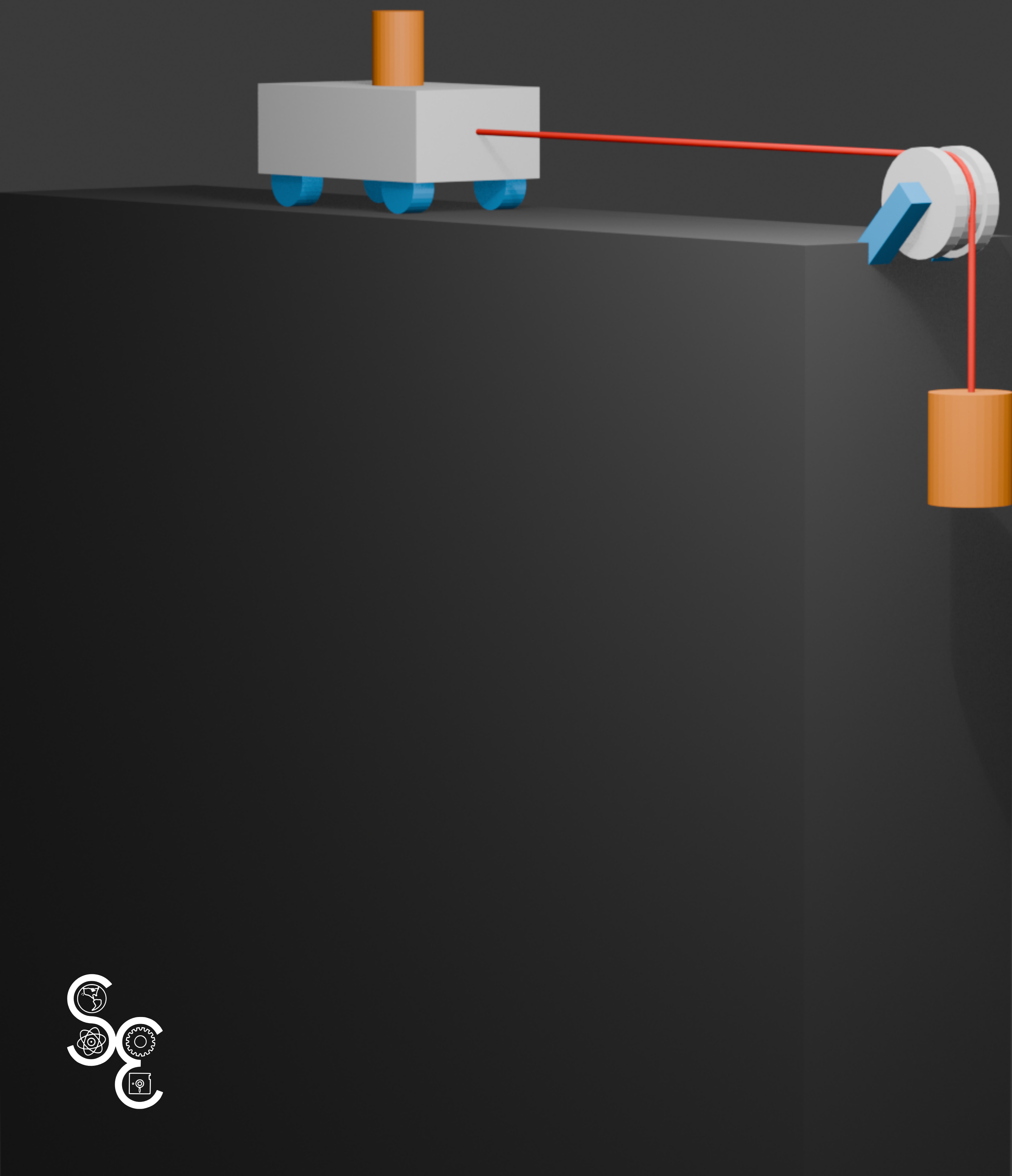

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From the cover: Newton's second law relates force, mass, and acceleration and is often written as $\sum \vec{F} = m\vec{a}$. In this special issue of Journal of Science & Engineering, researchers considered the validity of Newton's second law. *Cover image: Rishith Kilaru.*

String pulls cart down track
Weight provides a downward force
$\vec{F}$ equals $m\,\vec{a}$

Miguel Arenas, Callie Butash, Jake Chin, Kriti Malhotra,
Grace Nealon, and Petra Rofman

Testing Newton's second law in an accelerating system

Miguel Arenas,* Callie Butash, Jake Chin, Kriti Malhotra, Grace Nealon, and Petra Rofman
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
(Dated: December 6, 2024)

Newton's second law claims that force is the product of mass and acceleration ($\sum F = ma$). It could be of great use when calculating the acceleration, and thus velocity and position, of a system based on the external forces acting on it; therefore we tested its validity. Using a cart and pulley system, we examined the relationships between force, mass, and acceleration. The observed system accelerations for different values of force and mass were consistent with Newton's second law.

I. INTRODUCTION

Force is the product of mass and acceleration:

$$\sum F = ma, \tag{1}$$

where $\sum F$ is the sum of the external forces acting on the system in N, m is the mass in kg, and a is the acceleration in $\mathrm{m\,s^{-2}}$. (1) illustrates how a system's forces depend on the object's mass and acceleration.

This relationship between force, mass, and acceleration is useful in determining the acceleration that acts on an object without access to information that can be used to calculate acceleration using kinematics equations (eqs 2, 3, and 4) like initial (v_0) and final velocity (v_f) measured in $\mathrm{m\,s^{-1}}$, time (t) measured in s, and initial (x_0) and final position (x_f) measured in m.

$$x_f = x_0 + v_0 t + \frac{1}{2}at^2 \tag{2}$$
$$v_f = v_0 + at \tag{3}$$
$$v_f^2 = v_0^2 + 2a(x_f - x_0) \tag{4}$$

To facilitate hypotheses, we set up a system with a cart on a track attached by a string and pulley to a hanging mass (depicted in Fig. 1), allowing force and mass to be varied somewhat independently since some of the mass in the system was subject to gravitational force, while some were not.

We considered the acceleration, force, and mass, and hypothesized that there could be no acceleration in the system. Newton's first law gives us the static case where

$$H_0 : \sum F = 0. \tag{5}$$

Alternatively, we hypothesized that the net force would increase as the mass increased and that the acceleration of the system would decrease as mass increased, therefore the force would increase as the acceleration increased, while acceleration and mass have an inverse relationship (6):

$$H_1 : \sum F = ma. \tag{6}$$

* Contact author: 426marenas@frhsd.com

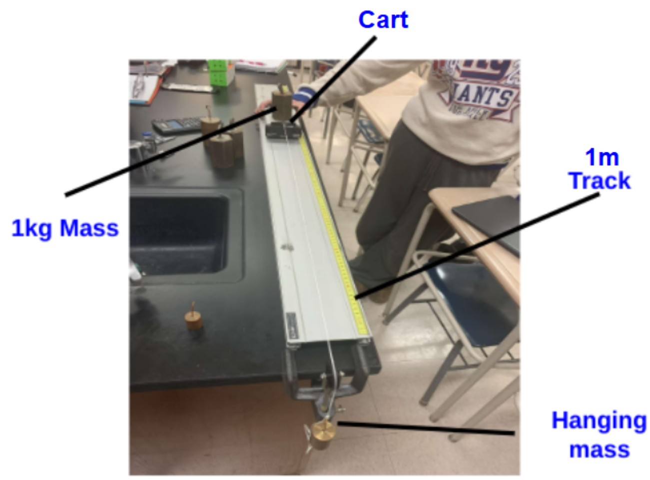

FIG. 1. Track, cart, and pulley system used for experiments. Total track length 1.0m.

Or, we hypothesized that either Newton's laws wouldn't apply, or something was erroneous with the considered forces, resulting in the force being equal to un-modeled forces acting that have a significant effect on acceleration (7) and (8).

$$H_2 : \sum F \neq 0, \tag{7}$$
$$H_3 : \sum F \neq ma. \tag{8}$$

These hypotheses were tested through a total of six trials, with a cart that had a constant weight, and different masses on the other end of the pulley. The time was measured to calculate the relationships between force, mass, and acceleration for both values of hanging mass.

II. METHODS AND MATERIALS

A. Tests

Tests ($n = 6$) were conducted using a track, cart, and pulley system (Fig. 1). The system included a 1.0 m

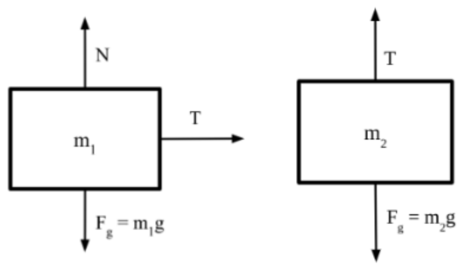

FIG. 2. Free body diagrams for m_1 (left) and m_2 (right) created in Google Drawings.

aluminum test track (Pasco Scientific; Roseville, CA) clamped to a table. The system was outfitted with a wheeled cart (Pasco Scientific; Roseville, CA) with ball bearings and knife-edge wheels. The cart's mass was 0.493 kg and it carried a 1.000 kg mass for a total mass of 1.493 kg. Attached to the cart was a string that looped over a pulley clamped to the table. On the other side of the string, for the first three trials, was a 0.050 kg mass, which was swapped out for a 0.200 kg mass for the last three trials. The hanging masses provided gravitational force to drive the system. The cart was released from rest and allowed to accelerate. We measured the time it took for the cart to move from rest 0.70 m along the track. Data were logged in a Google Document (Google; Mountain View, CA) on a school-issued Google Chromebook (Google; Mountain View, CA).

B. Acceleration calculations

The acceleration predicted under Newton's second law (1) can be calculated using the tensions of each mass. As seen in Fig. 2, the mass on the track moving horizontally is m_1 and the mass falling is m_2. The track is frictionless, so the force acting on m_1 equals the tension and is calculated as

$$F_1 = m_1 a = T. \tag{9}$$

The tension is also acting upward on m_2, yielding

$$F_2 = -m_2 a = T - m_2 g. \tag{10}$$

Combining (9) and (10) and manipulating gives the system acceleration a as a function of gravitational acceleration g and the known masses m_1 and m_2:

$$a = \frac{m_2}{m_1 + m_2 + m_c} g. \tag{11}$$

$m_c = 0.493\,\mathrm{kg}$ accounts for the empty mass of the cart. Comparison of this estimate for a to measured values allows us to test the validity of (1).

The measured time data were used to calculate acceleration via kinematics assuming uniform motion [1]:

$$x = x_0 + v_0 t + \frac{1}{2} a t^2. \tag{12}$$

Selecting $x_0 = 0$ and recognizing $v_0 = 0$ when starting from rest, (12) can be solved for acceleration:

$$a_{meas} = \frac{2x}{t^2}, \tag{13}$$

where $x = 0.70\,\mathrm{m}$ is the length of the track, and t is measured during each trial.

III. RESULTS

Table I shows the measured time t for the system to move from rest to 0.7 m as well as the resulting acceleration calculated via (13), as hanging mass m_2 was varied between 0.050 kg to 0.200 kg. Total cart mass $m_1 + m_c = 1.493\,\mathrm{kg}$. All values are listed as mean ± one standard deviation with $n = 3$ replicates for each value of m_2.

TABLE I. Measured time t for the system to move from rest to 0.7 m as well as the resulting acceleration calculated via (13), as hanging mass m_2 was varied between 0.050 kg to 0.200 kg. Total cart mass $m_1 + m_c = 1.493\,\mathrm{kg}$. All values are listed as mean ± one standard deviation with $n = 3$ replicates for each value of m_2.

m_2 (kg)	t (s)	a_{meas} ($\mathrm{m\,s^{-2}}$)
0.050	2.31 ± 0.10	0.26 ± 0.02
0.200	1.00 ± 0.16	1.46 ± 0.41

Fig. 3 shows the measured acceleration for each trial (13) compared to the system acceleration predicted using (11). Measured values are in good agreement with predictions based on (13) and (1).

IV. DISCUSSION

A. Can we confirm that $\sum F = ma$ through experimentation?

Our trials demonstrated that as the hanging mass m_2, or the resulting gravitational force exerted on the system, increases, the system's acceleration increases. This supported our hypothesis $\sum F = ma$ (6). The force acting on the system increased by increasing the hanging mass m_2. The experimental data corroborated the hypothesis because the increased pulley mass and acceleration illustrate a direct relationship between force and acceleration. Our data showed a consistent pattern where an increase in the mass of the pulley increased the net force creating

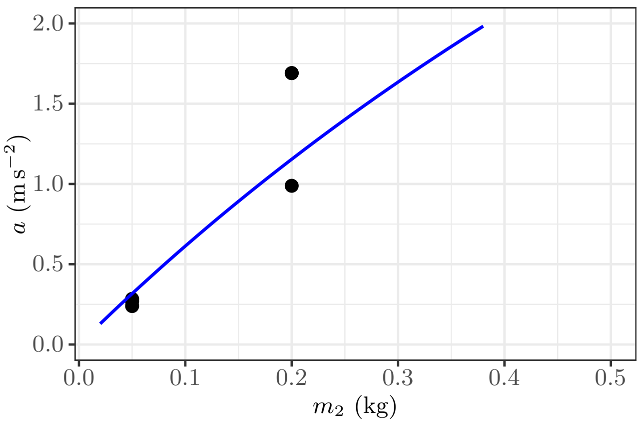

FIG. 3. Measured acceleration (a_{meas}) for each of the three trials, from (13) and Table I is shown by black dots for hanging mass $m_2 = 0.050\,\mathrm{kg}$ and $0.200\,\mathrm{kg}$. Predicted acceleration a based on (11) is shown by the blue line.

an increase in acceleration. This suggests that acceleration and force are proportional, in the case that mass is held constant (6). In our experiments, total system mass was $m_1 + m_2 + m_c$, which increased slightly, resulting in the curve of Fig. 3.

B. Sources of experimental error

A potential source of experimental error stems from the movement of the track between trials. This caused slight differences in tension, potentially affecting the calculated acceleration of the cart. Additionally, the person's timing was not consistent across all trials, nor were they randomized or rotated methodically by trial. This could result in small inconsistencies with the timing that may skew the results of calculating acceleration using a formula involving time or any other calculations involving time. In further testing, the time can be measured with sensors or videos to be more accurate. Furthermore, the expected acceleration was calculated assuming the string was massless and that friction had no effect on the cart. Since the experiment used a string with mass and since a frictionless system is impossible to achieve practically, this could result in possible differences between the experimental and expected acceleration.

V. ACKNOWLEDGMENTS

We thank several anonymous reviewers who provided thoughtful comments on our manuscript; Sir Issac Newton for the discovery of his three laws of motion; and Antonella Ortega for her momentum writeup as a reference.

PR wrote the abstract, introduction, test description, part of the discussion, and recorded data during the trials. MA created graphs of the results and helped describe them and draw conclusions. CB made the free-body diagrams and momentum track diagrams, computed acceleration, and wrote aspects of the discussion and parts of other sections. KM wrote the discussion and part of the results, noted the materials, timed the trials, and recorded the results. JC wrote about the sources of the experimental error and helped collect data and the abstract. GN led the track's setup, wrote out the procedures, and conducted each trial when we collected data. Everyone contributed to editing, proofreading, and assisting others with the sections they worked on.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

Verifying Newton's second law: the relationship between force, mass, and acceleration

Dia Avalur,* Srilekha Dantu, Jophy Lin, and Anika Tokala
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
(Dated: December 6, 2024)

This experiment investigates the relationship between mass, net force, and acceleration in accordance with Newton's second law of motion. A cart was set up on a near-frictionless plane with a pulley system and accelerated by a constant pulling force generated by a 0.100 kg weight. For each of six mass configurations, three trials were conducted, recording the time taken for the cart to travel a fixed distance of 0.800 m. Acceleration was calculated independently for each trial to capture variability, with averages and standard deviations computed as additional supporting evidence. Results demonstrated a clear inverse relationship: the average acceleration decreased from approximately 1.70 $\mathrm{m\,s^{-2}}$ at 0 g to 0.57 $\mathrm{m\,s^{-2}}$ at 1.000 kg, with low standard deviations indicating consistency across trials. For the 0 g mass confiiguration, calculated acclerations for individual trials ranged from 1.37 $\mathrm{m\,s^{-2}}$ to 1.93 $\mathrm{m\,s^{-2}}$, while for the 1.000 kg mass, accelerations ranged from 0.44 $\mathrm{m\,s^{-2}}$ to 0.66 $\mathrm{m\,s^{-2}}$. These findings confirm an inverse relationship between mass and acceleration under a constant force, aligning with Newton's prediction that $\sum \vec{F} = m\vec{a}$ and supporting the law's applicability in controlled experimental settings.

I. INTRODUCTION

Newton's second law of motion describes the relationship between force, mass, and acceleration [1]:

$$\sum \vec{F} = m\vec{a}, \tag{1}$$

where $\vec{F}$ is the force in newtons (N), m is the mass in kilogram (kg), and $\vec{a}$ is the acceleration in $\mathrm{m\,s^{-2}}$. For a given force, an object's acceleration is inversely proportional to its mass. As mass increases, the acceleration decreases [1]:

$$\vec{a} = \frac{\sum \vec{F}}{m}. \tag{2}$$

The significance of (1) lies in its ability to predict how objects will accelerate when subjected to different forces.

We seek to verify Newton's second law and hypothesize that as the mass of the cart increases, the acceleration will decrease, consistent with (2). To test this hypothesis, we conducted multiple trials in which known masses were placed on the cart, and a constant force was applied via a 0.1 kg weight. By comparing the accelerations for different masses, we examined the relationship between mass and acceleration to verify Newton's second law [1].

II. METHODS AND MATERIALS

A. Cart acceleration tests

Acceleration tests ($n = 18$) were conducted using a one-dimensional cart system along a fixed 0.800 m track. The experimental setup included a wheeled cart with a base mass of $m_c = 0.500$ kg and a near-frictionless track (both PASCO Scientific; Roseville, CA) to ensure consistent performance with minimal resistance for accurate measurements. Additional masses of $m_1 =$ 0.020 kg, 0.050 kg, 0.100 kg, 0.200 kg, 0.500 kg and 1.000 kg were used to vary the cart's total mass. Hanging mass $m_2 = 0.100$ kg was suspended using the pulley to apply a constant gravitational force on the system.

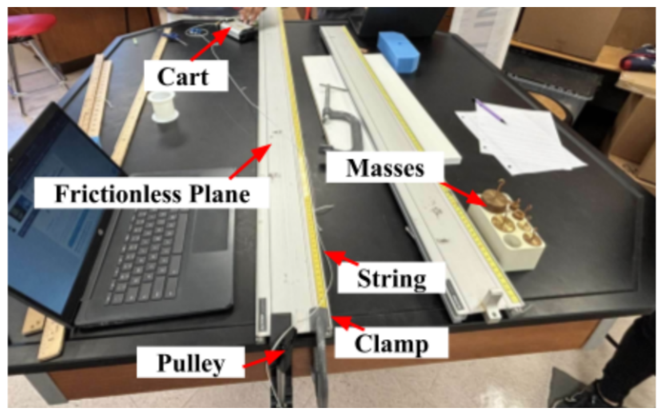

FIG. 1. Cart system consisting of a low friction 0.8 m track with a 0.500 kg wheeled cart; additional masses m_1, and a pulley system with a hanging mass m_2.

The cart was released from a designated starting point 0.800 m from the endpoint, and the time taken to travel the distance was recorded using a stopwatch with 0.01 s precision. Each mass configuration was tested in three separate trials to account for measurement variability. For each setup, the average time and corresponding standard deviation were calculated from the three trials to summarize the timing data, presented as mean ± one standard deviation [2].

* Contact author: 426davalur@frhsd.com

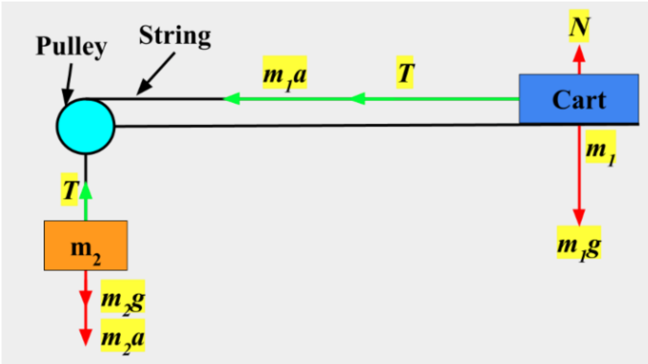

FIG. 2. Free body diagram of the cart system in Fig. 1. The cart (m_1) is connected to a hanging mass (m_2) through an ideal string, which is hung over a pulley, with forces labeled to represent the tension (T), gravitational force (mg), and normal force (N) acting on the system. Friction is assumed to be negligible.

B. Analyses of acceleration

To calculate the acceleration from our measurements, we used kinematics assuming uniform acceleration [1]:

$$a_{meas} = \frac{2d}{t^2}, \tag{3}$$

where a is the acceleration, $d = 0.800\,\mathrm{m}$ is the distance traveled, and t is the time taken for the cart to travel that distance.

We compared our measurements to the acceleration predicted by analysis of the free body diagram in Fig. 2 [1]:

$$a_{pred}(m_1) = \frac{m_2}{m_1 + m_2 + m_c} g, \tag{4}$$

where m_2 is the hanging 0.100 kg mass providing a constant gravitational force on the system, $g = 9.81\,\mathrm{m\,s^{-2}}$ is the gravitational acceleration, and $m_c = 0.5\,\mathrm{kg}$ is the empty mass of the cart. Independent variable m_1 is the additional mass in the cart in kg, which we varied from 0 kg to 1.000 kg in order to probe the relationship between F, m, and a.

III. RESULTS

Table I summarizes the measured time t for the cart to travel 0.8 m from rest, along with the resulting acceleration a from (3). $n = 3$ for each value of m_1; the hanging mass $m_2 = 0.1\,\mathrm{kg}$, and the empty cart mass $m_c = 0.5\,\mathrm{kg}$ so that the total accelerating system mass is $m_1+m_2+m_c$. Results are shown as mean ± one standard deviation.

Fig. 3 presents the relationship between acceleration a and mass m_1 for the cart system under the constant applied force.

TABLE I. Measured time (s) for cart to travel 0.8 m from rest, and corresponding acceleration ($\mathrm{m\,s^{-2}}$) for varying values of m_1. Hanging mass $m_2 = 0.1\,\mathrm{kg}$, empty cart mass $m_c = 0.5\,\mathrm{kg}$; total accelerating system mass is $m_1 + m_2 + m_c$. $n = 3$ replicates for each value of m_1. Results are shown as mean ± 1 s.d.

m_1 (kg)	t (s)	a_{meas} ($\mathrm{m\,s^{-2}}$)
0.000	0.98 ± 0.09	1.70 ± 0.29
0.020	1.03 ± 0.08	1.53 ± 0.23
0.050	1.15 ± 0.03	1.21 ± 0.07
0.100	1.18 ± 0.03	1.16 ± 0.06
0.200	1.26 ± 0.06	1.01 ± 0.09
0.500	1.33 ± 0.04	0.91 ± 0.06
1.000	1.68 ± 0.19	0.58 ± 0.12

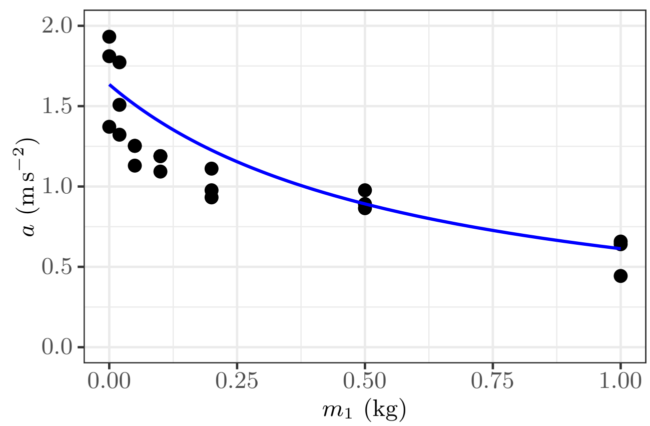

FIG. 3. Measured system acceleration a_{meas} as a function of m_1 using (3) shown by dots; blue line indicates the resulting system acceleration predicted by (4). Hanging mass $m_2 = 0.100\,\mathrm{kg}$; empty cart mass $m_c = 0.500\,\mathrm{kg}$. Total accelerating system mass is $m_1 + m_2 + m_c$.

IV. DISCUSSION

A. Is Newton's second law verified?

As observed in Table I, increasing the mass on top of the cart generally resulted in an increase in the time taken to travel the set distance of 0.80 m. For example, with 0.020 kg, the time recorded across three trials ranged from 0.95 s to 1.10 s. When the largest mass (1.000 kg) was added, the time increased, ranging from 1.56 s to 1.90 s. These individual trial results provide a reliable primary basis for analyzing the effect of mass on time and, subsequently, on acceleration. The trial data clearly show a trend of increasing time with added mass, consistent with Newton's second law [1].

The calculated accelerations, shown in Table I, further reinforce this relationship. By analyzing the individual acceleration values across the three trials for each mass, a clear inverse relationship between mass and acceleration emerges. For instance, with 0.020 kg, the acceleration values across trials ranged from approximately $1.32\,\mathrm{m\,s^{-2}}$ to $1.77\,\mathrm{m\,s^{-2}}$. As the mass increased to 1.000 kg, the acceleration values dropped significantly, ranging from approximately $0.44\,\mathrm{m\,s^{-2}}$ to $0.66\,\mathrm{m\,s^{-2}}$ across trials. This inverse trend across individual measurements strongly supports Newton's second law, where a constant force applied to an increasing mass yields lower acceleration [1].

Fig. 3 further corroborates this trend by plotting individual acceleration values for each trial against the theoretical predicted curve. The individual data points closely follow the expected inverse relationship–for all three trials, as mass increases, acceleration decreases–although some slight deviations from the predicted curve are observed. These minor discrepancies likely result from experimental errors such as slight variations in the release of the cart or timing precision, which will be discussed later. Despite these small deviations, the consistent downward trend in acceleration as mass increases validates the predicted inverse relationship and strongly aligns with Newton's second law [1].

Our findings (Fig. 3; (3) and (4)) demonstrate a consistent inverse relationship between mass and acceleration under constant force. This strong, inverse trend, even in the presence of minor experimental deviations, provides compelling support for Newton's second law, illustrating that as mass increases, acceleration decreases proportionally [1].

B. Sources of experimental error

While the track used in this experiment was near-frictionless, it is essential to acknowledge that some friction is unavoidable. The near-frictionless plane was chosen to minimize the effects of friction on the acceleration measurements, as a lot of friction can introduce significant experimental error by opposing the motion of the cart. Despite this, tiny variations in friction could still have influenced the results.

Timing inaccuracies likely introduced error due to the manual use of a stopwatch, especially at higher masses where precise measurement was required over longer intervals [3]. To improve accuracy, we could use an automated timing system, such as photogates, which would eliminate human reaction time errors and provide precise start and stop measurements [4]. This change would ensure that timing measurements are consistent and highly accurate across trials.

Additionally, slight inconsistencies in the cart's release, such as variations in initial positioning or angle, may have affected the measurements. To fix this, we could use a mechanical release mechanism to standardize the release process [4]. Such a mechanism would ensure that the cart starts from the exact same position and orientation in each trial, minimizing variability due to manual handling. This adjustment would help control for any small discrepancies caused by differences in the release method, leading to more reliable acceleration data.

V. ACKNOWLEDGEMENTS

We thank several anonymous peer reviewers for helping us to revise our lab and providing valuable, constructive feedback.

DA timed each trial during the experiment and assisted in writing the lab report. JL recorded the data for the experiment, performed the data calculations, created the figures, and also assisted in writing the report. SD prepared the experimental setup and managed the string during each trial. AT tested each weight individually and released the cart in each trial.

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Investigating Newton's first law in a pulley system

Andrew Barone,* Alexander Gut, Rishith Kilaru,† and Shrikar Swami
Manalapan High School, Englishtown, NJ 07726 USA

(Dated: December 6, 2024)

This experiment examined how force, mass, and acceleration relate in a one-mass pulley system. We measured the force acted upon a spring (Equivalent to the Tension in the spring) and compared it to the weight of the mass used in the experiment, factoring in Earth's gravity rounded to $-9.81\,\mathrm{m\,s^{-2}}$ By securing one end of the spring scale and the other end to the string attached to the mass, we tested whether the measured force matched what we expected based on the mass and gravity. Our results showed that the tension in the system changed depending on the total mass hanging. This supports the inverse relationship between mass and acceleration described by statics, e.g. $\sum F = 0$, which highlights how forces balance to prevent movement under certain conditions.

I. INTRODUCTION

This experiment explores Newton's first law, when the sum of all forces in a system is zero [1, 2]. We are using scenarios where we change masses. By securing one end of the spring scale to an object, and the other end to a string with the mass attached at a point beyond the pulley. The spring scale is calibrated by adding a known mass on the scale and zeroing it to be accurate. We can describe the relationship of force and mass with our results as they will, with this setup, illustrate how with an increase in mass there is a positive increase in force. If Newton's first law is correct, the spring scale will exert an equal and opposite force, resulting in equilibrium conditions with $\sum F = 0$ and no observable net movement.

To analyze the system, we use the equation:

$$T_1 = m_1 a_1 \tag{1}$$

where T_1 is the tension in the string (the force), m_1 is the mass of the various hanging masses, and a_1 is the Earth's gravitational acceleration. We will compare the theoretical results using a variety of masses, a_1 and this equation to create a theoretical force to compare with our experimental data; the force measured from the spring scale.

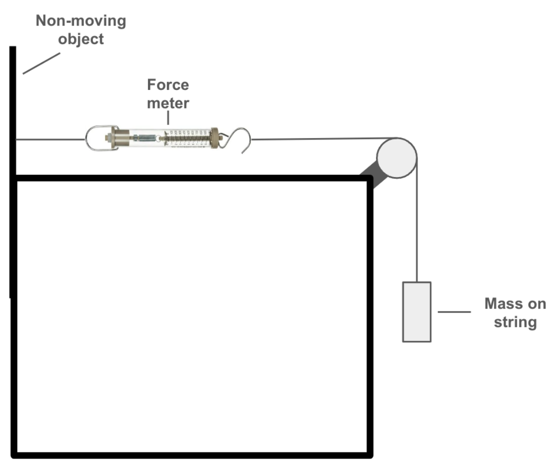

FIG. 1. Setup for the pulley system.

II. METHODS AND MATERIALS

Our tests were conducted using a spring, a hanging mass, and a pulley to change the direction of a string for added control of the objects (see Fig. 1). The materials used for this experimental setup were a complete scientific mass kit with a range of weights including 0.010 kg, 0.020 kg, 0.050 kg, 0.100 kg, 0.250 kg, 0.500 kg and 1.000 kg masses, a spring scale with a measurement range of 0 N to 20 N, an object that will not move to attach the force meter to, a pulley, an elevated surface about 0.8 m off the ground, and a string.

After calibrating the spring scale to provide a reliable number, we attached the pulley so that it is perpendicular to the surface. We anchored one end of the spring scale to a non-moving object and tied the other end to the string. The other end of the string was attached to a hanging mass, with the string fed over the pulley. These steps were repeated for each of the different masses used in the experimental trials.

To compare experimental and real-world values, we calculated the experimental force using (1). Plugging in our values, we obtained the tension in the string, representing the force on the spring scale, and then compared it to the recorded true value to check for consistency.

* Contact author: 425abarone@frhsd.com
† Contact author: 426rkilaru@frhsd.com; Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA

TABLE I. Measured relationship between mass on the string and weight (tension).

Mass on string (kg)	Weight of mass on string (N)
0.100	0.8
0.350	3.2
0.500	4.4
0.750	7.2
1.000	9.9
1.500	15.2
1.570	15.9
2.000	20.0

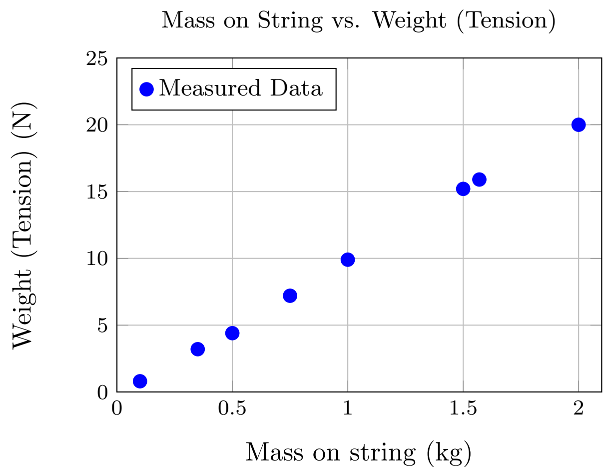

FIG. 2. Graph showing the roughly linear relationship between the mass on the string and the measured weight (tension).

III. RESULTS

Table I gives the measured relationship between the hanging mass on the string and the weight indicated by the spring scale, i.e. the tension in the string. These results are also shown in Fig. 2.

IV. DISCUSSION

Our results indicate that as the mass on the string increases the measured tension also increases in turn, confirming Newton's first law (Table I, Fig. 2). We observed a direct relationship between the mass and tension, as seen in Fig. 2. As the mass increased from 0.100 kg to 2.000 kg, the tension rose proportionally from 0.8 N to 20.0 N, confirming the predictions based on Newton's first law since the tension increases. The data is closely aligned with theoretical values of the weight force, showing consistent accuracy in the result. Minor deviations observed were due to to friction in the pulley and calibration imperfections in the spring scale, but had minimal impact on the overall trend. Overall, the findings support that, under constant gravitational acceleration, tension increases with mass.

Despite our attempts to simplify conditions, some factors may have affected our results, such as friction between the pulley and string (see Fig. 1) and slight differences in the expected and actual weights. Misalignment or reading errors with the spring scale may have also introduced inaccuracies. To reduce these issues in future experiments, recalibrating weights and lubricating surfaces would reduce the experimental error.

Overall, the results highlight how mass and force relate, showing that as mass increases, acceleration decreases under constant force. Real-world conditions, including reaction forces and limitations, should be considered to ensure accurate results.

V. ACKNOWLEDGMENTS

We acknowledge the valuable feedback from our peer reviewers, whose insights helped refine and strengthen our paper. AB led data collection and experimental trials; AG assisted with the data collection, trials, and experiment design; RK worked on setup, report formatting, and figures; and SS helped with the experiment design and setup.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004).

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Experimental support for Newton's second law

Cole Canada,* Stefano D'Agostino,† Ethan Fuks, Jason Katz, Ryan Leung, and Edmund Lee
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
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The purpose of this experiment is to investigate the relationship between the net force and the acceleration of a system. This system was composed of a cart carrying varying masses connected by a string over a pulley to a counterweight. For each cart mass, three trials were conducted, and the time required for the cart to travel 0.5 m was recorded. Acceleration was then calculated from this data. As the cart's mass increased, its acceleration decreased, which showed the inverse relationship between mass and acceleration as stated by Newton's Second Law. These findings confirm that acceleration depends on both net force and mass, as described by $\sum \vec{F} = m\vec{a}$.

I. INTRODUCTION

The equation $\sum \vec{F} = m\vec{a}$, commonly cited as Newton's second law, represents a principle first written down by Sir Isaac Newton [1] in his *Principia* (1687), a principle that offers an explanation to how the motion of macroscopic systems can change. The equation directly relates the acceleration of a chosen system to the net force on that system. Here, force and acceleration are vector quantities, allowing the above equation to be applied separately to any set of directions one chooses. Verifying Newton's second law as a reasonable model would be valuable for deriving the masses or accelerations of other bodies in nature.

If Newton's second law is not accurate within our experiment's degree of precision, we will reject it:

$$H_0 : \sum \vec{F} \neq m\vec{a}. \tag{1}$$

Alternatively, we provisionally accept that Newton's second law applies in our system:

$$H_A : \sum \vec{F} = m\vec{a}. \tag{2}$$

Here, we investigated the relationship between force, mass, and acceleration by conducting experiments using a two-mass pulley system. By setting up a cart connected to a hanging mass over a pulley and releasing it, the resulting acceleration of the carts and masses can then be observed and measured. We can test the null hypothesis H_0 using multiple trials comparing the cart's measured accelerations calculated via kinematics, to those predicted by net force equations originating from Newton's second law.

II. MATERIALS AND METHODS

The experiment used a 0.5 kg cart with low friction in its axles, allowing it to travel with minimal resistance across a smooth aluminum rail. In particular, the PASCO Dynamics Systems Basic Smart Cart Metal Track 1.2 m System and the PASCO Dynamics Systems Scientific ME-9454 Dynamic Collision Cart were used. The track was securely clamped to a level surface using Irwin trigger clamps. The cart, initially unloaded without any masses, was tied to a rope on the pulley with the small 0.020 kg mass attached to the end. Starting from the 0.3 m mark, the cart traveled to the 0.8 m mark, traveling a total distance of 0.5 m. A 0.5 kg mass was placed to indicate the stopping point. Three stopwatches and a metronome were used to time the different trials. These were used to improve the accuracy and reliability of timing measurements by syncing up the release of the cart and the start of the timers with the beat of the metronome. Trials were conducted three times per mass setting (1 kg, 2 kg, and 3 kg), incrementally adding 1 kg to the cart and keeping the small, hanging mass constant. This setup can be seen in Fig. 1.

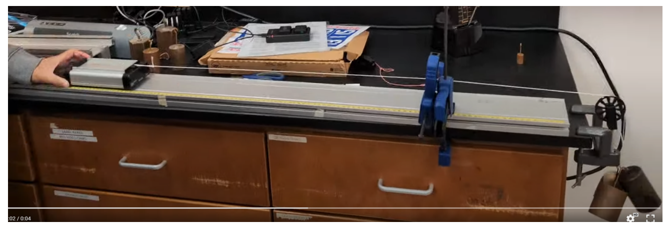

FIG. 1. Momentum track setup used

III. RESULTS

A plot of the average travel times for the cart and its load versus the mass of the cart and load is shown in Fig. 3. Note that each trial utilized three timers for each mass, and so each point is the mean of three times. Various regressions were fitted to the data (via the least square method; see section refsec:discussion), with the closest best-fit line shown in Fig. 3 (a square root regression).

Newton's Second Law (Experimental Method):

$$\sum \vec{F} = m\vec{a} \tag{3}$$

* Contact author: 426ccanada@frhsd.com
† Manalapan High School, Englishtown, NJ 07726

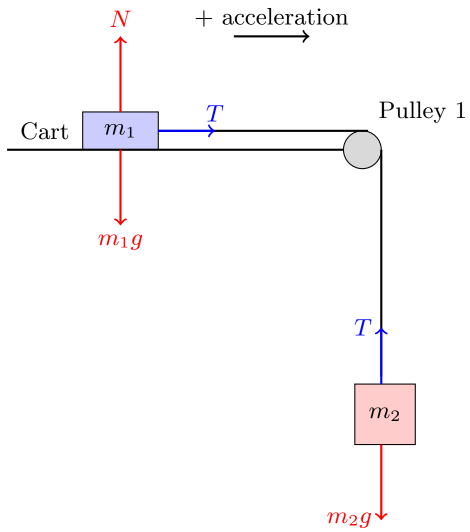

FIG. 2. Free Body Diagram of the System

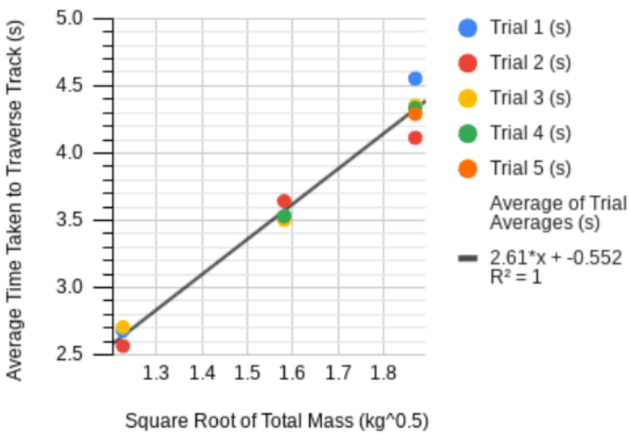

FIG. 3. Time to Accelerate 0.5 m vs. Mass of Cart/Weight System - Square Root Fit. Theoretical Relation: $t = (\sqrt{\frac{2\Delta x}{||\sum \vec{F}||}})(\sqrt{m})$

Kinematics (Baseline Method):

$$\vec{x}(t) = \vec{x}_0 + \vec{v}_0 t + \frac{1}{2}\vec{a}t^2 \tag{4}$$

Doing the calculations using a 1 kg weight will result in the following calculations (which correspond to the first cluster of points in Fig. 3:

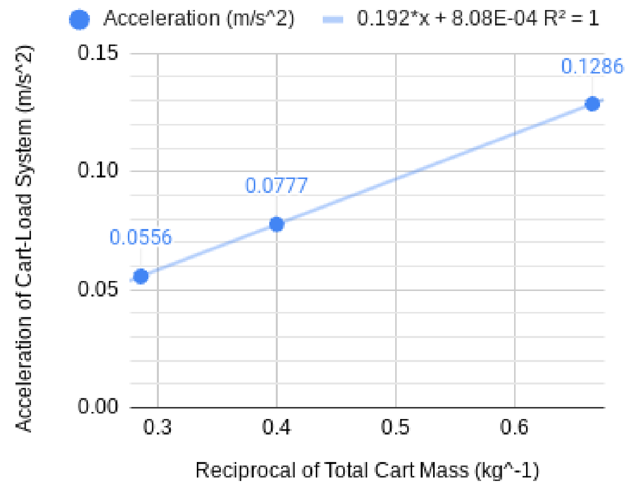

FIG. 4. Cart System Acceleration vs. Reciprocal Mass

Using our data in (4):

$$x(t) = 0.5m$$
$$x_0 = 0m$$
$$v_0 = 0m/s$$
$$t = 2.65s$$
$$0.5\text{m} = (0\text{m}) + (0\text{m/s})(2.65\text{s}) + \frac{1}{2}(a)(2.65\text{s})^2$$
$$a = (1/2.65)^2\text{m/s}^2$$
$$a = 0.1424\text{m/s}^2$$

A free body diagram (see Fig. 2) can be drawn of the system with the momentum cart (m_1) and the falling mass (m_2). A system of equations can be created by applying (3) to the vectors along the perpendicular axis indicated in Fig. 2. The string and pulley are assumed to have both negligible mass and friction, thus both tension forces are approximately equal, simplifying calculations. The calculation of a is shown below (for more on this system, see [2]).

$$m_1 = 1.5kg, \quad m_2 = 0.02kg, \quad g, = 9.8m/s^2$$
$$\sum \vec{F} = m\vec{a} \Rightarrow$$
$$T = m_1 a, \tag{5}$$
$$m_2 a = m_2 g - T \tag{6}$$
$$\Rightarrow T = m_2 g - m_2 a \Rightarrow m_1 a = m_2 g - m_2 a$$
$$\Rightarrow m_1 a + m_2 a = m_2 g \Rightarrow a(m_1 + m_2) = m_2 g$$
$$\Rightarrow a = \frac{m_2 g}{m_1 + m_2} \tag{7}$$
$$\Rightarrow a = \frac{0.02\text{kg} * 9.8\text{m/s}^2}{0.02\text{kg} + 1.5\text{kg}} \approx 0.129\,\text{m}\,\text{s}^{-2}$$

An a of $0.1424\,\text{m}\,\text{s}^{-2}$ calculated through kinematics and is relatively close to our a of $0.129\,\text{m}\,\text{s}^{-2}$ calculated through $\sum \vec{F} = m\vec{a}$. The percent error is:

$$\left|\frac{a_{calculated} - a_{experimental}}{a_{calculated}}\right| = \frac{0.1424m/s^2 - 0.129m/s^2}{0.1424m/s^2} \approx 0.094 = 9.4\% \tag{8}$$

just under 10%. Repeating the above calculations for 2 kg and 3 kg mass loads ($m_1 = 2.5$ kg and 3.5 kg, respectively) using both kinematics and force equations yields similar percent errors of about 2.1% and 4.2%, well within the acceptable 10% range for experimental uncertainty. Fig. 4 is a plot of these accelerations versus the cart system's mass.

IV. DISCUSSION

A. $t \sim \sqrt{m}$ as predicted by Newton's second law

The variables directly measured in the experiment (mass and time) were plotted in Fig. 3 with a corresponding square root regression. From the coefficient of determination in Fig. 3 ($R^2 = 1$), the data is consistent with direct proportionality between the time traveled and the square root of the cart system's mass. That proportionality comes from substituting the simplified kinematic relation between time and displacement $\Delta x = \frac{1}{2}at^2$ into Newton's Second Law (see Fig. 3 for exact relation). This is further supported by an R^2 value of 1 in Fig. 4, which directly suggests that the cart system's acceleration was directly proportional to its reciprocal mass as predicted by Newton's second law (where the constant of proportionality is $||\sum \vec{F}||$). As mentioned under section III, other regressions were tested to see whether they could fit the data better than square root and linear correlations, respectively, and thus invalidate the accuracy of Newton's second law. Exponential and logarithmic regressions, however, both had slightly poorer R^2 values for Fig. 3 data (0.998 and 0.994, respectively) and Fig. 4 data (0.992 and 0.989), suggesting that their high values are merely a result of insufficient data points. (Higher order polynomials will trivially have perfect correlations, and thus do not disprove our hypothesis).

B. Source of experimental error

The acceleration derived through (Newtonian) mechanics differed measurably from that calculated through kinematics due to several potential sources of experimental error. For one, more trials with different masses would be required to more definitively characterize the seemingly optimal regressions in Fig. 3 as square root and Fig. 4 as linear rather than exponential, logarithmic, or any other relationship. Also, the experimental set-up may have had significant friction in various places, such as axial friction in the wheels and pulley or static friction between the rope and the pulley, forces that were not accounted for when acceleration was calculated using Newton's second law. Axial friction, for example, would have rendered the tension forces acting on the cart and counterweight to be unequal, likely reducing the overall acceleration of the system. Another potential source of significant error was the human error associated with our timing methods. Instead of relying on the reaction speeds of the timers responding to the metronome, a more accurate method might have employed electronics (e.g. camera sensors) to ensure the timers began their stopwatches at the same exact instant that the cart was released.

V. CONCLUSIONS

In supporting Newton's second law, our findings reinforce the validity of a key part of classical mechanics by showing correlation between mass and acceleration. This knowledge helps us understand systems varying from moving cars to orbiting satellites, illustrating its utility in describing and predicting everyday phenomena, advanced engineering and design situations, and potentially many other scientific and technological fields. For example, Newton's second law is integral to mechanical engineering, where it informs the design of machinery and vehicles, and to civil engineering, where it helps with structural analysis and load distribution (by assuming acceleration in $\sum \vec{F} = m\vec{a}$ is zero), thus ensuring the stability of buildings and bridges. Moreover, confirming Newton's second law opens the way to developing more sophisticated and useful formalizations of mechanics that align with it.

VI. ACKNOWLEDGEMENTS

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CC, SDA, EF, JK, EL, and RL collected the data, analyzed the results and wrote the lab report.

[1] I. Newton, *Philosophiæ Naturalis Principia Mathematica* (S. Pepys, London, 1687).

[2] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

Newton's second law as demonstrated in a cart-pulley-mass system

Vasudevan Govardhanen,* Gage Grant, Aidan Dumalagan, Tushaar Akula, Daivik Jajoo, Rohan Avalur, Adrit Sikdar, and Jake Cacciarelli
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
(Dated: December 6, 2024)

We investigated the dynamics of a two-mass cart-pulley system to examine the relationship between mass distribution and acceleration in a nearly frictionless environment. Motion sensors tracked the cart's position along the track, allowing us to calculate velocity and acceleration over time. By systematically increasing the mass on the pulley, we observed corresponding increases in the cart's acceleration, enabling a comparison with theoretical predictions based on Newton's second law.

I. INTRODUCTION

Newton's second law of motion, asserts that the acceleration of an object is directly proportional to the net force acting upon it and inversely proportional to its mass [1]:

$$F = ma \tag{1}$$

where F is the net force applied to the object, m is its mass, and a is the resulting acceleration.

This experiment is designed to rigorously examine (1) by analyzing the dynamics of a cart-pulley-mass system. The system consists of a cart of mass m_1 connected to a pulley with a hanging mass m_2, with m_2 generating a net force $F = m_2 g$ due to gravity. On a frictionless track, the expected acceleration a of the cart can be expressed as:

$$a_{pred} = \frac{m_2 g}{m_1 + m_2} \tag{2}$$

where $g = 9.81\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity. (2) is obtained from application of Newton's second law and assumes that friction between the cart and track and within the pulley is negligible, that the pulley is massless, and that the string is massless and stiff. We systematically vary m_2 and measure the cart's displacement over time to calculate its observed acceleration, allowing for a comparison with predicted values from (2).

We hypothesize that the net applied force F is proportional to the resulting accceleration a of the cart, consistent with (1)':

$$H_1 : a \propto F. \tag{3}$$

Alternatively, we may observe that the system acceleration a is not related to the applied force, and is instead constant, in which case we would reject Newton's second law.

$$H_0 : a = a_0 \tag{4}$$

* Contact author: 426vgovardhanen@frhsd.com

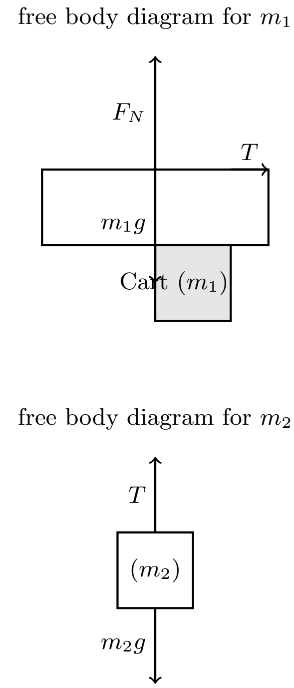

FIG. 1. Separate free body diagrams for cart m_1 and hanging mass m_2.

II. MATERIALS AND METHODS

Measurements were obtained using a small cart (PASCO Scientific; Roseville, CA) of mass $m_1 = 0.500\,\mathrm{kg}$. The cart was situated within a track (PASCO Scientific; Roseville CA) clamped to a lab bench; the cart and track were assumed to be frictionless. A string connected to the cart was hung over a pulley; the other end of the string was connected to varying masses $m_2 = 0.050\,\mathrm{kg}$, $0.070\,\mathrm{kg}$ and $0.100\,\mathrm{kg}$. m_2 was the independent variable, used to exert a varying external gravitational force $F = m_2 g$ on the system, where $g = 9.81\,\mathrm{m\,s^{-2}}$ [1]. The time t for the mass to travel distance $d = 0.50\,\mathrm{m}$ was measured by a human observer with a stopwatch with $0.01\,\mathrm{s}$ precision. One measurement was made for each value of m_2.

The measured system acceleration was then calculated

TABLE I. Measured values of t for different m_2, as well as the resulting system acceleration a, calculated using (5). $n = 1$ measurement for each value of m_2. For these measurements, $m_1 = 0.5\,\mathrm{kg}$ and $d = 0.5\,\mathrm{m}$.

m_2 (kg)	t (s)	a_{meas} ($\mathrm{m\,s^{-2}}$)
0.050	2.39	0.18
0.070	2.05	0.24
0.100	1.80	0.31

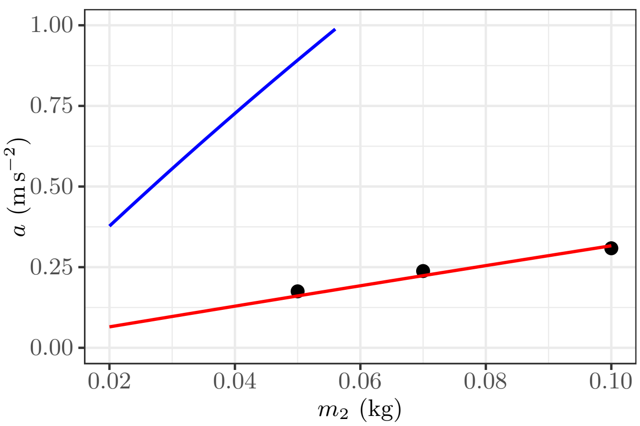

FIG. 2. Acceleration a as a function of m_2. Data from Table I. Measured values of acceleration from Table I and (5) are plotted as black dots; predictions from Newton's second law (2) shown as blue line. For these data, $m_1 = 0.500\,\mathrm{kg}$. The measured accelerations and the predictions do not agree well. The fit is much better for $m_1 = 2.5\,\mathrm{kg}$, shown as red line.

using

$$a_{meas} = \frac{2d}{t^2}. \tag{5}$$

(5) comes from simple kinematics under uniform, constant acceleration, recognizing that the system starts from rest so that $v_0 = 0$ and choosing $x_0 = 0$ [1]. The measured system acceleration from (5) can then be compared to the acceleration predicted by (2) based on Newton's second law (1).

III. RESULTS

Table I gives the measured values of t for different m_2, as well as the resulting system acceleration a. The results of Table I are also plotted in Fig. 2.

IV. DISCUSSION

The experimental results did not support the theoretical predictions of Newton's second law (see mismatch in Fig. 2). While we did observe a trend where the acceleration increased as the mass of the hanging weight increased, the predicted values of acceleration differed from those we measured by a factor of three or more. Possible explanations for this discrepancy are that we failed to correctly measure the mass of the cart or to include the dead weight of the cart or of any masses loaded into the cart; or that there is a significant amount of friction in the system. In particular, when we recalculate for $m_1 \sim 2.5\,\mathrm{kg}$ we observe better agreement between the measured acceleration and those predicted by (2) (red line, Fig. 2). We also attribute our discrepancies to various real-world factors such as friction between the cart and track, which was assumed to be negligible in the idealized theoretical model, mass of the pulley and friction within it, and other experimental limitations such as timing errors or air resistance.

V. ACKNOWLEDGEMENTS

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[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

Examining the relationship between the net force and acceleration in a pulley system

Siddharth Kedharnath,* Samay Prabhu,† Daniel Altman, and Joel D'Souza
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
(Dated: December 6, 2024)

This experiment tested Newton's second law of motion, $F = ma$, by examining the relationship between the applied force, the mass of a system, and its resulting acceleration. A cart was placed on a rail and connected to a hanging mass via a pulley system. By varying the hanging mass, the experiment allowed for changes in both the total system mass and the applied force. This design provided a range of conditions under which the relationship between force, mass, and acceleration could be analyzed. Measurements of the applied gravitational force from the hanging mass and the cart's acceleration were used to evaluate if the acceleration matched theoretical predictions based on $F = ma$. Results showed a proportional relationship between force and acceleration for a given mass, supporting Newton's second law.

I. INTRODUCTION

Newton's second law of motion[1] states that the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. This relationship can be mathematically expressed as:

$$F = ma \tag{1}$$

where F is the net force applied to an object, m is its mass, and a is the resulting acceleration. In this experiment, we investigate the relationship between net force and acceleration using a simple cart system. The system consists of a cart of constant mass m_1, connected to a pulley system that allows for varying hanging masses m_2 to be attached, which exert external gravitational force mg on the system. By manipulating m_2 as the independent variable, and measuring the time t taken for the cart to travel a known distance $d = 0.65\,\mathrm{m}$, we can measure the acceleration of the cart a (dependent variable) for different net forces applied.

In the context of our setup (see Fig. 2), the acceleration of the cart can be expressed by the equation:

$$a = \frac{m_2 g}{m_1 + m_2} \tag{2}$$

where m_2 is the hanging mass, $g = 9.81\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity, and m_1 is the mass of the cart. (2) is valid for the free body diagram shown in Fig. 1, assuming there is no friction between the cart and track or in the pulley, and that the mass of the string and pulley are negligible [1]. The numerator in (2) is the applied external force $m_2 g$, while the denominator is the total system mass subject to acceleration, $m_1 + m_2$. A full derivation of (2) using Newton's second law is given in Appendix .

We hypothesize that as the net force acting on the cart increases due to the addition of weights, the acceleration of the cart will also increase, demonstrating a direct proportionality between net force and acceleration as stated in Newton's second law [1]:

$$H_1 : a \propto F. \tag{3}$$

Or as a null hypothesis, we may observe that there is no significant relationship between the net force acting on the cart and the acceleration of the cart; the acceleration remains constant regardless of changes in net force, in which case we would reject Newton's second law:

$$H_0 : a = k. \tag{4}$$

By comparing our measured acceleration a as the force (via m_2) is varied, we can test these two hypotheses.

II. METHODS AND MATERIALS

To test our hypotheses, we used the experimental setup pictured in Fig. 2 and shown in the free body diagrams of Fig. 1. The setup included a small wheeled cart (PASCO Scientific; Roseville, CA) with additional mass so that $m_1 = 0.780\,\mathrm{kg}$. The cart rolled within a small track (PASCO Scientific; Roseville, CA); we assumed the friction in the cart and track system to be negligible. The cart was connected to a string (assumed to be massless) that was fed over a pulley to hanging mass m_2, which was varied systematically ($m_2 = 0.020\,\mathrm{kg}$, $0.050\,\mathrm{kg}$, $0.100\,\mathrm{kg}$, $0.200\,\mathrm{kg}$ and $0.500\,\mathrm{kg}$) in order to vary the applied external gravitational force on the system. The system was allowed to accelerate from rest and the time t for the system to move $d = 0.65\,\mathrm{m}$ was measured by a human observer using a stopwatch with $0.01\,\mathrm{s}$ precision as well as video recordings.

The measured acceleration a of the cart was then calculated using the kinematic equation:

$$a = \frac{2d}{t^2}, \tag{5}$$

which assumes constant uniform acceleration; it comes from the simple kinematics equation solved for a [1]. The

* Contact author: 426skedharnath@frhsd.com
† Contact author: 426sprabhu@frhsd.com

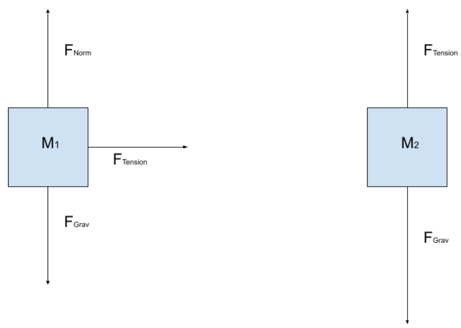

FIG. 1. Free body diagram

FIG. 2. Physical Setup

measured acceleration was then compared to the acceleration predicted by (2) in order to test the validity of Newton's second law.

III. RESULTS

Table I gives the time t to travel from rest a distance $d = 0.65\,\mathrm{m}$, for each different value of m_2. For these data, $m_1 = 0.780\,\mathrm{kg}$.

The data of Table I are plotted in Fig. 3, which shows the measured acceleration a as a function of the nondimensionalized mass $\frac{m_2}{m_1+m_2}$, plotted as black dots. The blue line shows a linear regression acceleration predicted by (2) is also shown as a blue line.

TABLE I. Summary of trial data.

m_2 (kg)	t (s)	a ($\mathrm{m\,s^{-2}}$)
0.020	2.35	0.24
0.050	1.45	0.62
0.100	1.20	0.90
0.200	0.79	2.08
0.500	0.62	3.38

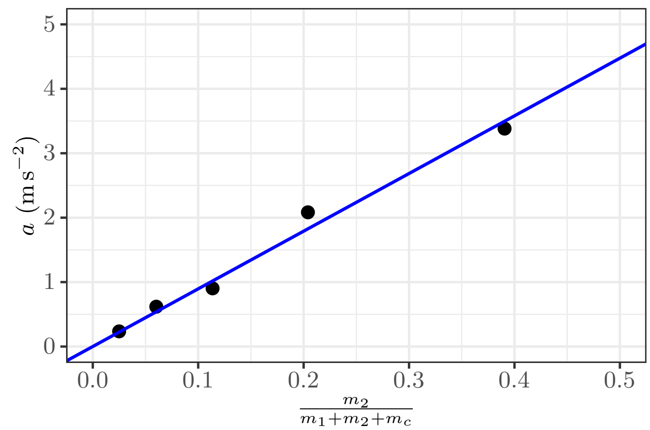

FIG. 3. Graph of mass ratio vs acceleration. Measured a from Table I and (5) shown as black dots. Blue line shows linear regression (slope=$8.95\,\mathrm{m\,s^{-2}}$, $p = 1.25\times10^{-5}$, $d.f. = 4$). Linear regression with a non-zero intercept term showed the intercept is not significantly different from zero ($p = 0.66$).

IV. DISCUSSION

A. Proportional relationship and validation of Newton's second law

Fig. 3 demonstrates a clear linear relationship between the mass ratio $\frac{m_2}{m_1+m_2}$ and the acceleration a. As the mass ratio increases, the acceleration increases proportionally, consistent with the theoretical model of (2). The data points closely follow the expected trend, and the slope of the best-fit line ($8.95\,\mathrm{m\,s^{-2}}$ is roughly consistent with the expected value of the gravitational constant $g = 9.81\,\mathrm{m\,s^{-2}}$). Small deviations from the line may be attributed to measurement errors, such as timing inaccuracies or frictional losses in the cart and pulley system.

While there are minor discrepancies between the calculated and predicted values, the results are generally in agreement, validating the proportionality between the applied force and acceleration as predicted by Newton's second law. The linear relationship observed in Fig. 3 supports (linear regression, $p = 1.25 \times 10^{-5}$, $d.f. = 4$) that our hypothesis H_1, Newton's second law $\sum F = ma$.

V. SOURCES OF EXPERIMENTAL ERROR

The actual acceleration observed in the experiment may have been slightly lower than predicted due to the effects of friction between the cart and the track, as well as air resistance acting on the system. These factors reduce the net force acting on the cart and could explain why our observed slope was slightly less that the expected value of $g = 9.81\,\mathrm{m\,s^{-2}}$.

The accuracy of the recorded time for each trial is affected by human reaction time when using a stopwatch. This introduces a small amount of error that could influence the precision of the calculated acceleration. To reduce this error, automated timing devices or motion sensors could be employed in future experiments, ensuring more consistent and accurate timing measurements.

The pulley system itself may introduce some resistance due to friction or mechanical inefficiencies, which would slightly reduce the net force experienced by the cart. This could contribute to a smaller acceleration than theoretically expected, and future experiments could attempt to minimize these losses by using a more efficient pulley system.

VI. CONCLUSION

This experiment successfully illustrates the direct relationship between net force and acceleration in a pulley system, affirming Newton's second law [1] in a practical setup. The data clearly demonstrate that as net force on the cart increases, so does its acceleration, supporting our hypothesis and highlighting the predictable nature of classical mechanics.

For future extensions, teams could investigate the effects of additional variables, such as frictional forces by using various surfaces under the cart, or examine the impact of pulley efficiency by experimenting with different pulley materials and designs. These modifications would offer a more comprehensive understanding of real-world factors that influence force and acceleration relationships in mechanical systems.

VII. ACKNOWLEDGMENTS

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SP measured data such as masses, distance traveled, and time for cart to reach end of rail, assisted in the physical setup of the lab and checked over the calculations, wrote multiple parts of the lab as well as concluded the results. SK assisted in the measuring of data, completed calculations, and setup of the physical lab, wrote multiple parts of the lab as well and concluded the results. JDS setup the physical aspects of the lab and performed the main calculations for all the data needed. DA measured data for more accurate results and constructed free body diagrams and assisted in the derivation of the acceleration formula.

Appendix: Derivations of formulae

1. Acceleration of a half-Atwood machine assuming Newton's second law is valid

To derive the formula for the acceleration a of the system in Fig. 1, we analyze the forces acting on both m_1 and m_2. For m_1, the only horizontal force acting on it is the tension T in the string, leading to the equation:

$$T = m_1 a. \tag{A.1}$$

For m_2, the forces acting on it are the downward force due to gravity ($m_2 g$) and the upward tension T in the string, thus:

$$m_2 g - T = m_2 a. \tag{A.2}$$

We substitute (A.1) into (A.2) to eliminate T and simplify:

$$m_2 g - m_1 a = m_2 a, \tag{A.3}$$
$$m_1 a + m_2 a = m_2 g, \tag{A.4}$$
$$a(m_1 + m_2) = m_2 g. \tag{A.5}$$
$$\tag{A.6}$$

Solving for a gives the acceleration of the system as predicted by Newton's second law::

$$a = \frac{m_2 g}{m_1 + m_2}. \tag{A.7}$$

2. Kinematic equation for constant acceleration

The kinematic equation for an object undergoing uniformly accelerated motion is given by:

$$d = v_0 t + \frac{1}{2} a t^2, \tag{A.8}$$

where d is the displacement, v_0 is the initial velocity, a is the acceleration, and t is time. If the object starts from rest, the initial velocity is $v_0 = 0$. We are also free to chose $x_0 = 0$. (A.8) simplifies to

$$d = \frac{1}{2} a t^2. \tag{A.9}$$

Rearranging to solve for a, we get:

$$a = \frac{2d}{t^2}. \tag{A.10}$$

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004).
[2] R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria (2024) .

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Relationship between Newton's second law and acceleration, mass, and force

Nitika Kishore,* Sameera Patil, Anton Lavrenov, and Connor Paszkiewicz
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
(Dated: December 6, 2024)

Using a pulley system with two different masses on either end, this experiment focuses on the relationship between force and acceleration, taking into account various masses. Via the experiment results, we found that Newton's second law, $\sum F = ma$, was consistent with our measurements.

I. INTRODUCTION

Newton's second law of motion is $\sum F = ma$ [1], which states that the force is directly proportional to acceleration. If a force is applied to an object and a force of equal magnitude is applied to a second object, then the object with more mass will accelerate less [1]. Furthermore, Newton's second law states that as acceleration increases, mass should decrease and vice versa. Our goal throughout this experiment was to test how accurate that is by changing various masses used in our cart-pulley system. If Newton's second law is accurate, $F = ma$ should always stay accurate and constant. We hypothesize that the acceleration should decrease as the masses increase. We also hypothesize that the force of the system ($F = ma$) should stay constant as the weight values on the cart changes.

II. MATERIALS AND METHODS

Our method of testing Newton's Second Law consisted of a pulley system, where there were two weights: one hanging weight as well as a weight on the cart above (see Fig. 1). Our hanging weight was 0.5 kg and our weights on the cart (0.5 kg) varied between 1.2 kg, 2.4 kg, and 3.6 kg. Our method for measuring acceleration was timing how fast it took our cart to travel 0.50 m once released using a measuring tape and stopwatch. We assumed that the friction caused by our plane and pulley were negligible. We conducted multiple trials, changing the weights on the cart for each one. We then found acceleration using the formula

$$a = \frac{m_{hang}}{m_{cart} + m_{hang} + 0.5} g, \tag{1}$$

where a is acceleration, m_{hang} is the hanging mass, m_{cart} is the mass added to the cart, and 0.5 kg is the cart's empty mass). Finally, we found the forces acting on the system per trial using $\sum F = ma$.

* Contact author: 426nkishore@frhsd.com

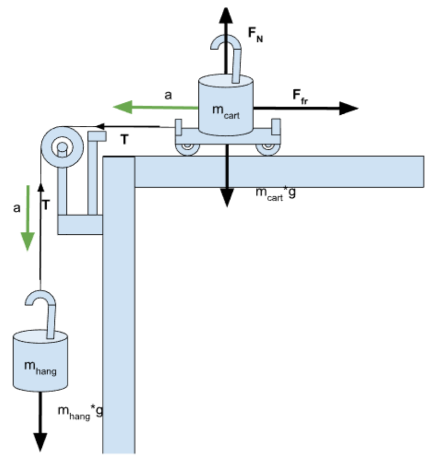

FIG. 1. Experiment Setup FBD

TABLE I. Table caption here.

m_1 (kg)	t (s)	a (m s^{-2})
1.200	0.87	1.32
2.400	1.23	0.66
3.600	1.35	0.55

III. RESULTS

Table I gives the measured time and resulting acceleration for each value of m_1. Fig. 2 shows a plot of the results from Table I as black dots. The predicted acceleration from (1) is shown as a blue line. The measured and predicted accelerations agree well.

IV. DISCUSSION

Fig. 2 shows that as mass increases, the rate at which acceleration decreases becomes smaller. This correlates with our hypothesis as acceleration is inversely proportional to the total mass in our setup. Despite the changing variables, net force was able to remain constant throughout the entire experiment, supporting our hypothesis that Newton's second law is always true and consistent.

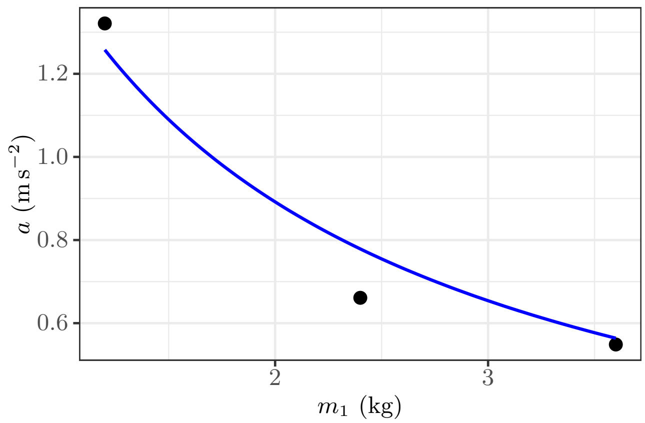

FIG. 2. Total Mass (kg) x Acceleration (m s^{-2})

A. Sources of experimental error

Variability in force of the system could be due to friction and how it affects acceleration as well, as we assumed it was negligible. Human error occurring during the timing of the experiment could have also affected our results and in turn, the force of the system.

V. ACKNOWLEDGMENTS

We thank several anonymous reviewers for comments that improved the manuscript. We also thank Manalapan High School for providing us with all the materials used throughout this experiment.

NK timed the experiment, and worked on experiment set-up, original lab report design, and final revisions, AL performed analysis of the data and the figures. CP worked on original lab report revisions and documentation of initial data collection. SP worked on initial lab experiment report design, abstract and conclusion, and the description of the procedure.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

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Testing Newton's second law with cart and mass

Sharone Krasnopolsky,* Timur Neyir, and Brady Gorelczenko
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA
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Newton's second law states that force equals mass times acceleration ($F = ma$). In our experiment, we used varying masses attached to a cart and pulley system in order to examine the relationship between mass, acceleration, and force. We found that the relationship between force and acceleration is proportional, supporting Newton's second law.

I. INTRODUCTION

Newton's second law of motion states that acceleration of an object is directly proportional to the net force acting on that object and is inversely proportional to its mass [1]:

$$F = ma, \tag{1}$$

where F is the net force, m is the mass, and a is the acceleration. In this experiment, we investigate the relationship between force, mass, and acceleration by analyzing the motion of a cart while it is being pulled over a pulley by a hanging mass. By varying the mass of the hanging mass, we examine how the change in force impacts the cart's acceleration. We hypothesize that if the mass of the hanging weight is increased, then the acceleration of the cart will increase proportionally, in accordance with Newton's second law of motion, which states that acceleration is directly proportional to the net force applied and inversely proportional to the mass of the object.

II. METHODS AND MATERIALS

The experiment used a 0.500 kg PASCO collision cart and a 1.2 m long PASCO aluminum dynamics track as shown in Fig. 1. We used a 0.200 kg weight, a 0.500 kg weight, a 1.000 kg weight, a 1.200 kg weight, and a 1.500 kg weight as our hanging weights. In addition, we also used a PASCO "super pulley with mounting rod" (Fig. 2) as a pulley and a string to connect the weight to the cart. Our procedure started with setting up the track with the cart on top and the pulley hanging off the side as shown in Fig. 1 and Fig. 2.

We attached the 0.200 kg weight to the cart and pulled the cart back 0.45 m from the pulley. The cart was then released and was allowed to freely accelerate until it reached the end of the track. In total, we took three trials for each of the five weights (0.200 kg, 0.500 kg, 1.000 kg, 1.200 kg and 1.500 kg) for a total of 15 trials. During the trials, we measured the amount of time it took for the cart to travel 0.45 m and recorded the data. Using the data, we calculated the tension force exerted on the cart using the formula $F = ma$. To calculate the acceleration, we used the equation $a = 2d/t^2$ to find the acceleration.

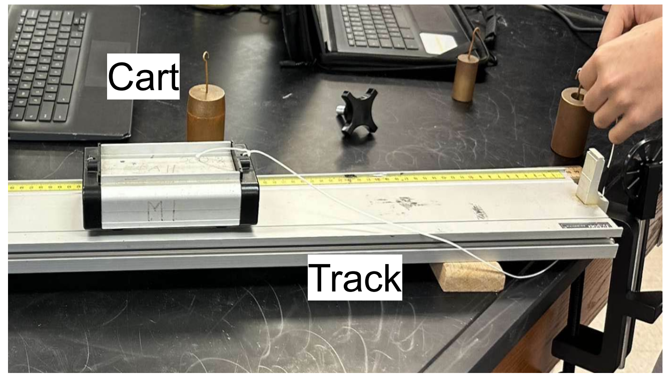

FIG. 1. Track used in experiment

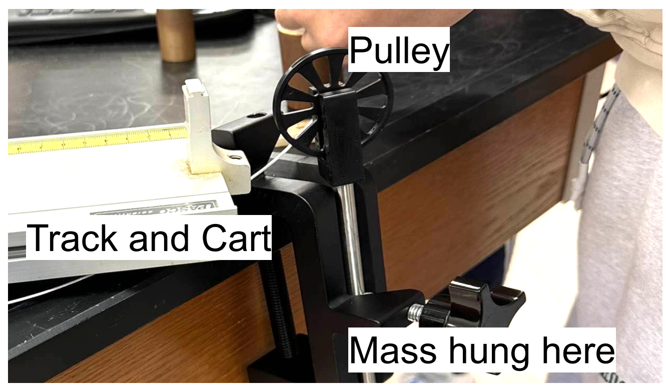

FIG. 2. Pulley where string is pulled, on the left is the cart, on the right, masses are hung

III. RESULTS

By taking the average times for each mass, we perform the equation $d = \frac{1}{2}at^2$, which can be rearranged into, $a = 2d/t^2$ to calculate the acceleration of the cart, as shown in Table I.

The results in Table I are plotted in Fig. 4, which shows the mass of the weight and time it took for the cart to reach the end of the track. The resulting accelerations

* Contact author: 426skrasnopolsky@frhsd.com

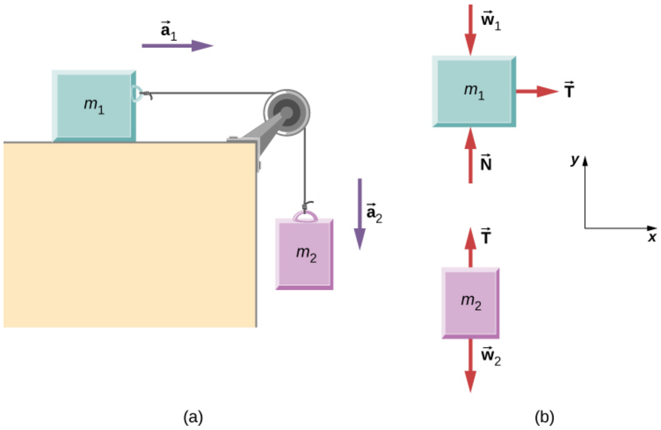

FIG. 3. Free-Body Diagram of the system in motion utilizing an ideal pulley, from https://pressbooks.online.ucf.edu/phy2048tjb/chapter/6-1-solving-problems-with-newtons-laws/

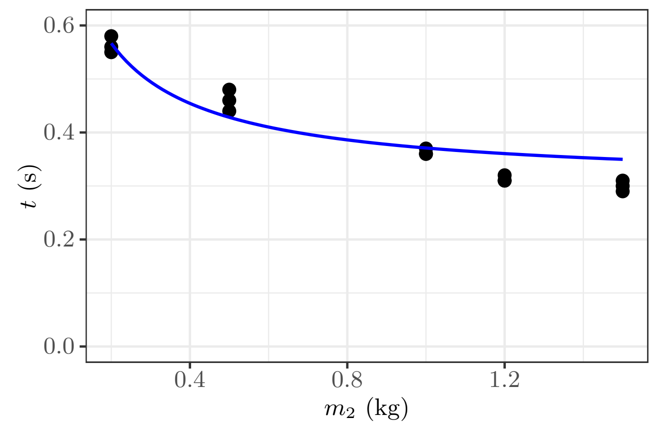

FIG. 4. Graph that shows the mass of the weight (x) and time it took for the cart to reach the end of the track (y)

TABLE I. Time t for each mass, and measured acceleration a. All values listed as mean $\pm$ one standard deviation for $n = 3$ replicates for each value of m_2.

m_2 (kg)	t (s)	a ($\mathrm{m\,s^{-2}}$)
0.200	0.56 ± 0.02	2.84 ± 0.15
0.500	0.46 ± 0.02	4.27 ± 0.37
1.000	0.36 ± 0.01	6.82 ± 0.21
1.200	0.31 ± 0.01	9.17 ± 0.33
1.500	0.30 ± 0.01	10.0 ± 0.7

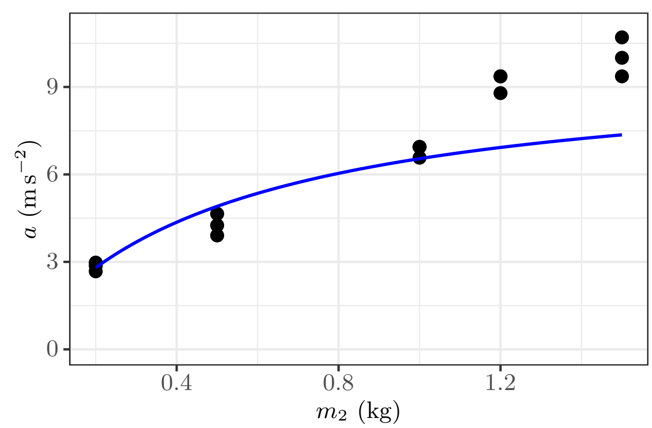

FIG. 5. Graph that shows the mass of the weight (x) and acceleration (y)

are plotted in Fig. 5. The blue lines show the predictions for the fre body diagram given in Fig. 4, $a = \frac{m_2}{m_1+m_2}g$.

IV. DISCUSSION

In this experiment, we investigated Newton's second law, $F = ma$, by examining how varying weights influenced the acceleration of a cart. Our data demonstrates a strong proportional relationship between force and acceleration, with calculated values aligning closely with theoretical predictions as seen in Figs. 4 and 5.

The slight discrepancies between theoretical and experimental force values can be attributed to friction on the track, which likely reduced the net force acting on the cart. Additionally, timing inaccuracies over short distances may have introduced minor errors in measuring the acceleration. Pulley inefficiencies, such as resistance or string tension losses, could also have contributed to the observed deviations. These could be especially pronounced at the highest levels of m_2, where forces are high and times are short.

These findings validate Newton's second law while highlighting areas for improvement in the experimental setup. Implementing a frictionless track, using a more precise timing mechanism, and optimizing the pulley system could help achieve results that more closely match theoretical values.

V. ACKNOWLEDGEMENTS

We thank several anonymous reviewers for their helpful comments on our manuscript.

SK set up the track, measured the time it took for the cart to travel 0.45 m, and wrote the abstract, introduction, methods and materials, and acknowledgements. TN also helped set up the track, recorded the results, did all calculations, and wrote results and discussions. BG helped prepare experiment materials and helped with pre-trial measurements.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

Experimental investigation of Newton's second law using a two-mass pulley system

Andrew Fox,* Brandon Heller, Dev Parekh, Joshua Perle,† and Clay Stevens
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA

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This study investigates Newton's second law of motion, $F = ma$, through a two-mass pulley system. The experiment aimed to measure the relationship between the applied force and the resulting acceleration while considering the system's total mass. A wheeled cart (m_1) was connected to a hanging mass (m_2) by a nearly massless string over a low-friction pulley. The cart's acceleration was measured as it traveled along a horizontal track, and both theoretical and experimental accelerations were calculated for comparison. Initially, our results did not match predictions of Newton's second law. Significant discrepancies between acceleration values were observed, which we attribute to friction between the cart and the track. When we accounted for friction by including an explicit $\mu = 0.03$ term, we saw good agreement. This work demonstrates the validity of Newton's second law within experimental uncertainty.

I. INTRODUCTION

Newton's second law of motion states that the net force F acting on an object is equal to the product of its mass m and its acceleration a:

$$F = ma \tag{1}$$

(1) predicts that, for a given mass, the acceleration of an object is directly proportional to the applied net force.

The experiment involved a two-mass pulley system consisting of a wheeled cart (m_1) on a horizontal track connected via a string to a hanging mass (m_2) that provides gravitational force to accelerate the cart. By recording the time it takes the cart to travel a known distance, the acceleration of the system was determined and compared to the theoretical acceleration predicted by Newton's second law. This approach allowed us to assess whether the observed motion adhered to theoretical expectations.

We hypothesized that the experimentally measured acceleration and force would match theoretical values. Discrepancies could arise from friction, timing inaccuracies, or assumptions such as the pulley and string being idealized as frictionless and massless, respectively.

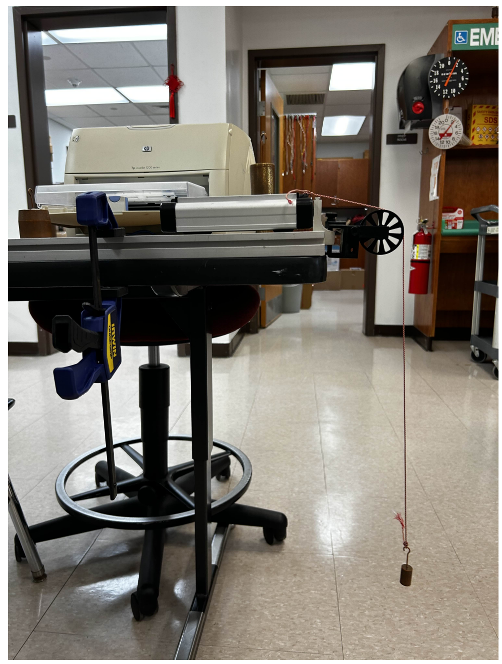

FIG. 1. Experimental setup: (1) wheeled cart ($m_1 = 0.5042\,\mathrm{kg}$), (2) hanging mass ($m_2 = 0.020\,\mathrm{kg}$), (3) low-friction pulley, (4) horizontal track (0.40 m test length).

II. METHODS AND MATERIALS

The experimental apparatus consisted of a wheeled cart ($m_1 = 0.5042\,\mathrm{kg}$, PASCO Scientific; Roseville, CA) placed on a horizontal, low-friction track (PASCO Scientific; Roseville, CA). A string, which we model as massless, connected the cart to a hanging mass ($m_2 = 0.020\,\mathrm{kg}$), which provided the force to accelerate the system. The string was passed over a pulley with minimal rotational friction. The length of the track was measured to be 0.40 m, and a stopwatch with 0.01 s precision was used to record the time it took for the cart to traverse this distance. The experiment was repeated five times to ensure consistency. The setup is shown in Fig. 1, with all components labeled.

For each trial, the system was released from rest, and the cart's motion along the 0.40 m track was manually timed with a stopwatch. For each trial, the time was recorded, and the process was repeated for five trials. Care was taken to ensure that the track and pulley system were as low friction as possible.

To calculate the measured acceleration, a_{meas}, we used the kinematics equation for constant, uniform accelera-

* Manalapan High School, Englishtown, NJ 07726 USA
† Contact author: 426jperle@frhsd.com

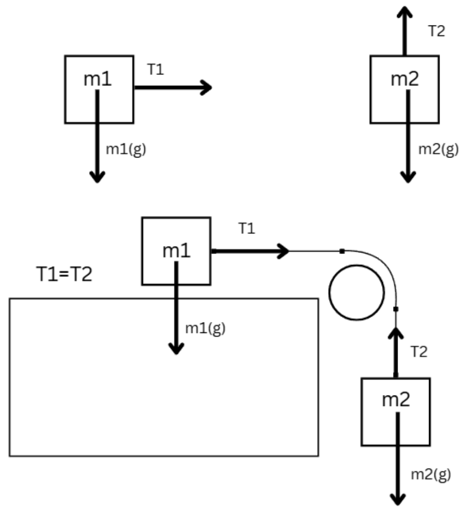

FIG. 2. Free body diagram of the experimental setup pictured in Fig. 1.

tion from rest [1] and solved for a:

$$a_{\text{meas}} = \frac{2d}{t^2}, \tag{2}$$

where $d = 0.40\,\text{m}$ is the distance traveled and t is the measured time in s.

Fig. 2 shows a free body diagram of the experimental setup. For this configuration, [1] gives the system acceleration a_{theory} obtained by applying Newton's second law ($F = ma$) to both m_1 and m_2 and simplifying, recognizing the tension T in the string and the accelerations of each mass must be the same:

$$a_{\text{theory}} = \frac{m_2}{m_1 + m_2} g, \tag{3}$$

where $g = 9.81\,\text{m}\,\text{s}^{-2}$ is the acceleration of gravity. (3) shows the external net force acting on the system is $m_2 g$, while the total system mass that is accelerating is $m_1 + m_2$ [1]. If comparison of measured accelerations (2) and the acceleration predicted by Newton's second law (3) reveals a mismatch, we either reject Newton's second law or examine if additional forces are acting on the system.

III. RESULTS

Table I summarizes time t (s) for the cart to travel from rest 0.40 m, and measured accelerations a_{meas} obtained using (2). Measurements are given as mean ± one standard deviation. $n = 6$ measurements for $m_1 = 0.5042\,\text{kg}$ and $m_2 = 0.020\,\text{kg}$.

Theoretical acceleration (blue line, Fig. 3) was calculated using (3) to be $0.374\,\text{m}\,\text{s}^{-2}$, which is about three times the measured acceleration of $(0.0988 \pm 0.0008)\,\text{m}\,\text{s}^{-2}$. We attribute the differences between theoretical and experimental results were attributed to timing inaccuracies, rotational resistance in the pulley, and friction between the cart and track.

TABLE I. Time t (s) for the cart to travel from rest 0.40 m, and measured accelerations a_{meas} obtained using (2). Measurements are given as mean ± one standard deviation. $n = 6$ measurements for $m_1 = 0.5042\,\text{kg}$ and $m_2 = 0.020\,\text{kg}$.

m_1 (kg)	t (s)	a ($\text{m}\,\text{s}^{-2}$)
0.5042	2.85 ± 0.01	0.0988 ± 0.0008

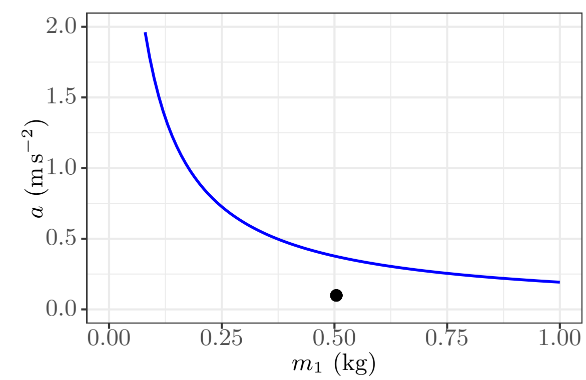

FIG. 3. Measured accelerations from Table I shown as black dots; theoretical prediction from (3) shown as a blue line. For these data, $m_1 = 0.5042\,\text{kg}$ and $m_2 = 0.020\,\text{kg}$. The factor of three discrepancy between measurement and theory may be due to friction between the cart and the track.

IV. DISCUSSION

A. Newton's second law not supported

The experimental data did not support Newton's second law, as the observed accelerations ($a_{meas} = (0.0988 \pm 0.0008)\,\text{m}\,\text{s}^{-2}$ were not consistent with Newton's second law theoretical predictions ($a_{theory} = 0.374\,\text{m}\,\text{s}^{-2}$) within the precision of our measurement. Discrepancies between (2) and (3), seen also in Fig. 3, arose due to unavoidable factors such as human error in timing, rotational resistance in the pulley, and friction between the cart and track.

B. Estimating the effect of friction in our system

In particular, the friction between the cart and track would be significant if the cart had failed bearings that increased the coefficient of friction μ substantially. In this case, (3) becomes

$$a_{friction} = \frac{m_2 - \mu m_1}{m_1 + m_2} g. \tag{4}$$

For $\mu = 0.03$, $a_{friction}$ calculated with (4) becomes $0.09\,\mathrm{m\,s^{-2}}$, which is nicely within our experimentally measured values $a_{meas} = (0.9880 \pm 0.0008)\,\mathrm{m\,s^{-2}}$.

Further experiments could enhance accuracy by using a cart with functioning bearings and employing photogates or motion sensors to measure time and acceleration with greater precision. Testing with multiple values of m_2 would provide additional data points to evaluate the proportionality of force and acceleration more rigorously than a check at a single operating point.

V. ACKNOWLEDGMENTS

We thank Manalapan High School for supplying the equipment and several anonymous reviewers for their helpful comments on our manuscript. We thank D Evangelista for suggesting that our observed discrepencies may be due to friction and assisting us in our analysis. AF managed the setup, BH and DP collected and analyzed data, CS performed the calculations, and JP prepared this report.

[1] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

Verifying $\sum \vec{F} = m\vec{a}$

Sagarika Yagnyeshwaran,* Emily Chen, Andrew Kabatsky,
Aleksandra Guimaraes, Vijita Ayyangar, and Aryanna Cetrulo
Science & Engineering Magnet Program, Manalapan High School, Englishtown, NJ 07726 USA

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Newton's second law is verified in this lab through the use of a cart and rail attached to a pulley system, tested with various masses on the cart and a constant hanging mass. Thus, if we know the force applied and the mass, we can use this equation to calculate the acceleration of an object. Conversely, if we can measure the acceleration and mass of an object, we can also compute the applied force. Our results were confirmed by the values obtained as a result of this experiment.

I. INTRODUCTION

Net force is the product of mass times acceleration [1]:

$$\sum \vec{F} = m\vec{a} \tag{1}$$

where $\vec{F}$ is the force produced in newtons (N), m is the mass in kilograms (kg), and $\vec{a}$ is the acceleration produced in meters per second squared ($\mathrm{m\,s^{-2}}$) [1]. (1) reflects that the force acting on an object involves both its mass and acceleration. Formally, force and acceleration are vector quantities; here we consider one-dimensional (1D) movements and will drop the vector notation for simplicity.

By applying Newton's second law, we can understand how different forces (gravity, friction, tension, etc.) affect motion. Understanding the relationship between force, mass, and acceleration lets us predict how objects will move under different forces. This helps engineers design systems with precise control over motion, ensuring the stability and safety of structures and vehicles.

Therefore, we wish to verify Newton's second law, $F = ma$. We hypothesize that an applied force on a cart system, of known mass, will produce an acceleration proportional to this force, assuming friction is negligible:

$$H_0 : F = ma \tag{2}$$

Alternatively, if F is not directly proportional to ma, we may observe deviations:

$$H_1 : F \neq ma \tag{3}$$

We tested these hypotheses by conducting numerous trials and recording the time taken for the cart to travel 0.7 m from rest as the mass of the mass on the cart changed.

* Contact author: 426syagnyeshwaran@frhsd.com

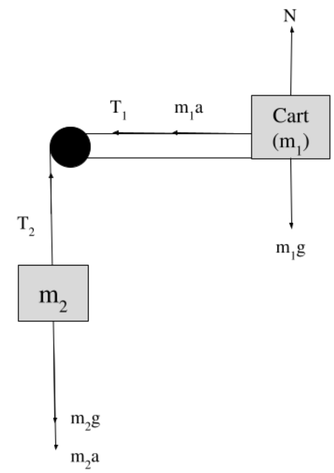

FIG. 1. Free body diagram of the system

II. METHODS AND MATERIALS

A. Finding acceleration

In the experiment, we weighed each of the masses on a spring scale (Learning Resources; Vernon Hills, IL), with each of the additional masses on the $m_c = 0.5$ kg cart being 1.2 kg, and the smaller hanging mass tied to the string being $m_2 = 0.2$ kg. We tied the smaller mass to a string and strung it across a pulley system, with the other end of the string tied to the cart. For each trial, the mass on the cart which was placed on top of a rail (PASCO Scientific; Roseville, CA) was increased and the time it took for the cart to travel 0.7 m was recorded. All trials started from rest.

We used a mass pulley system, with a hanging mass of 0.2 kg, with different masses on the cart (in addition to the cart's mass), starting from: 1.2 kg, 2.4 kg and 3.6 kg. We measured three different times for each trial, observing how fast it took the cart to travel a distance of 0.7 m so we could calculate the system's acceleration with different masses m_1 as the independent variable. For each trial, we used an iPhone 14 (Apple; Cupertino, CA) to take videos to obtain timing.

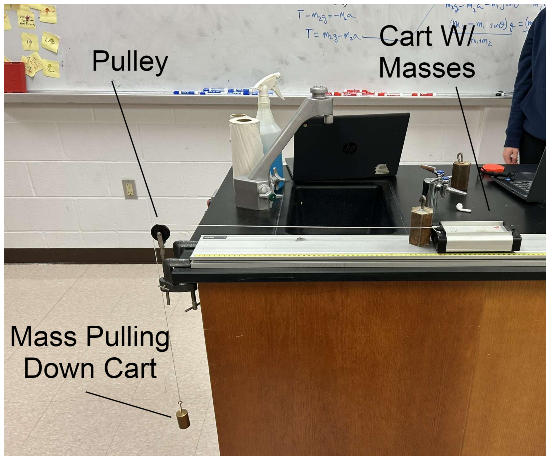

FIG. 2. Experimental setup showing the cart ($m_c = 0.5\,\mathrm{kg}$) system with additional mass m_1, string, pulley, and hanging mass $m_2 = 0.2\,\mathrm{kg}$ pulling the cart via the string. Pull distance was 0.7 m.

To calculate the measured acceleration of each individual trial for the respective masses, we assumed uniform acceleration and re-arranged the kinematic equation for position, solving for the acceleration a given the time t to move a distance d [2]:

$$a_{meas} = \frac{2d}{t^2}. \tag{4}$$

We compared the measured acceleration to the acceleration predicted using the masses of the system and the free body diagram given in Fig. 1, a half-Atwood machine configuration with solution commonly available in textbooks [2]:

$$a = \frac{m_2}{m_1 + m_2 + m_c} g \tag{5}$$

where the denominator indicates the total system mass is given by $m_1 + m_2 + m_c$ and $g = 9.81\,\mathrm{m\,s^{-2}}$ is the acceleration of gravity.

III. RESULTS

We measured the time taken for a cart to travel a set distance of 0.7 m. For each mass m_1, three trials were conducted. Table I gives the measured time and resulting acceleration, calculated using (5), listed as mean ± one standard deviation, for $m_1 = 1.2\,\mathrm{kg}$, $2.4\,\mathrm{kg}$ and $3.6\,\mathrm{kg}$. For these measurements, $m_2 = 0.2\,\mathrm{kg}$ and the empty cart $m_c = 0.5\,\mathrm{kg}$. For each value of m_1 there were $n = 3$ replicates.

Fig. 3 illustrates the behavior of the expected and calculated accelerations in terms of mass. Measured values of acceleration, calculated from t using (5) and tabulated in I, are plotted in Fig. 3 as black dots. Acceleration predicted using (5) is plotted as a blue line. The actual acceleration values follow the behavior of the predicted values closely, verifying Newton's second law. As the mass added to the cart increased, we observed a decrease in acceleration, while the force (T in Fig. 1) remained approximately the same. Specifically, the calculated accelerations were $1.33\,\mathrm{m\,s^{-2}}$, $0.67\,\mathrm{m\,s^{-2}}$ and $0.54\,\mathrm{m\,s^{-2}}$, and the forces were 1.756 N, 1.836 N and 1.870 N for masses of 1.7 kg, 2.9 kg and 4.1 kg (accounting for the cart and the added masses, i.e. $m_1 + m_c$) respectively.

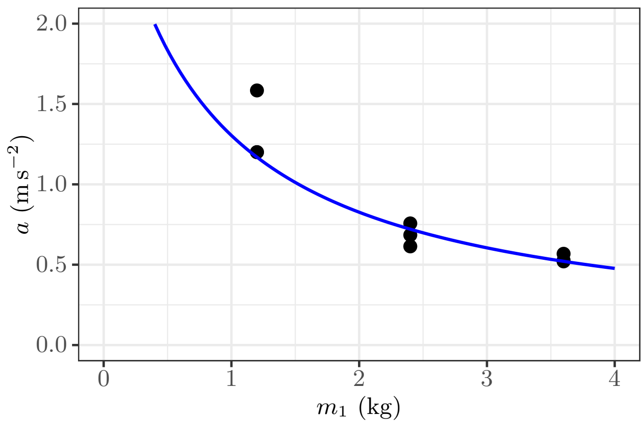

FIG. 3. Mass m_1 (kg) versus acceleration a ($\mathrm{m\,s^{-2}}$). Dots indicate measured values of acceleration obtained from the measured time to travel from rest 0.7 m using (4). $n = 3$ replicates for each value of m_1, as tabulated in Table I. Blue line indicates acceleration predicted by (5) for m_1, $m_2 = 0.200\,\mathrm{kg}$, and empty cart $m_c = 0.500\,\mathrm{kg}$.

For each of the trials, the standard deviations of the accelerations were minimal (Table I), indicating precise results.

IV. DISCUSSION

Our results support Newton's second law (1), showing the acceleration was inversely proportional to the total mass of the cart. As shown in Fig. 3, measured acceleration values align with acceleration predicted from Newton's second law (1) based on analysis of the free-body

TABLE I. Measured time t (s) and resulting acceleration a ($\mathrm{m\,s^{-2}}$), listed as mean ± one standard deviation, for $m_1 = 1.2\,\mathrm{kg}$, $2.4\,\mathrm{kg}$ and $3.6\,\mathrm{kg}$. For these measurements, $d = 0.7\,\mathrm{m}$, $m_2 = 0.2\,\mathrm{kg}$ and the empty cart $m_c = 0.5\,\mathrm{kg}$. For each value of m_1 there were $n = 3$ replicates.

m_1 (kg)	t (s)	a ($\mathrm{m\,s^{-2}}$)
1.200	1.03 ± 0.08	1.33 ± 0.22
2.400	1.43 ± 0.08	0.69 ± 0.07
3.600	1.61 ± 0.04	0.54 ± 0.03

diagram of Fig. 1, corroborating that mass and acceleration are inversely proportional to each other when force is kept the same. Our test was conducted with varying total system mass and constant force; however, if mass remains the same, acceleration and force will be directly proportional.

Ultimately, force calculations should be consistent as the mass increases, but we observed a slight discrepancy from our results compared to the expected values, likely due to human error in timing with stopwatches. As a result of minor errors during timing, the calculated acceleration values were slightly higher than the predicted acceleration values. This is visible in Fig. 3, where most of the measured acceleration values from the experiment are plotted slightly higher than the curve of the predicted acceleration. Though the plane was near frictionless, the little friction should have decreased the acceleration in comparison to the expected values; however, our human error was significant and offset the difference caused by friction.

V. ACKNOWLEDGEMENTS

We thank A Ortega for her momentum writeup which served as a reference. Additionally, we thank several anonymous reviewers whose comments improved our manuscript.

EC, AG, AK, and SY developed the first draft of the manuscript. VA, AC, AG, and AK collected the data. Everyone contributed to revisions.

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[2] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*, 5th ed. (W H Freeman and Company, New York, 2004) .

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