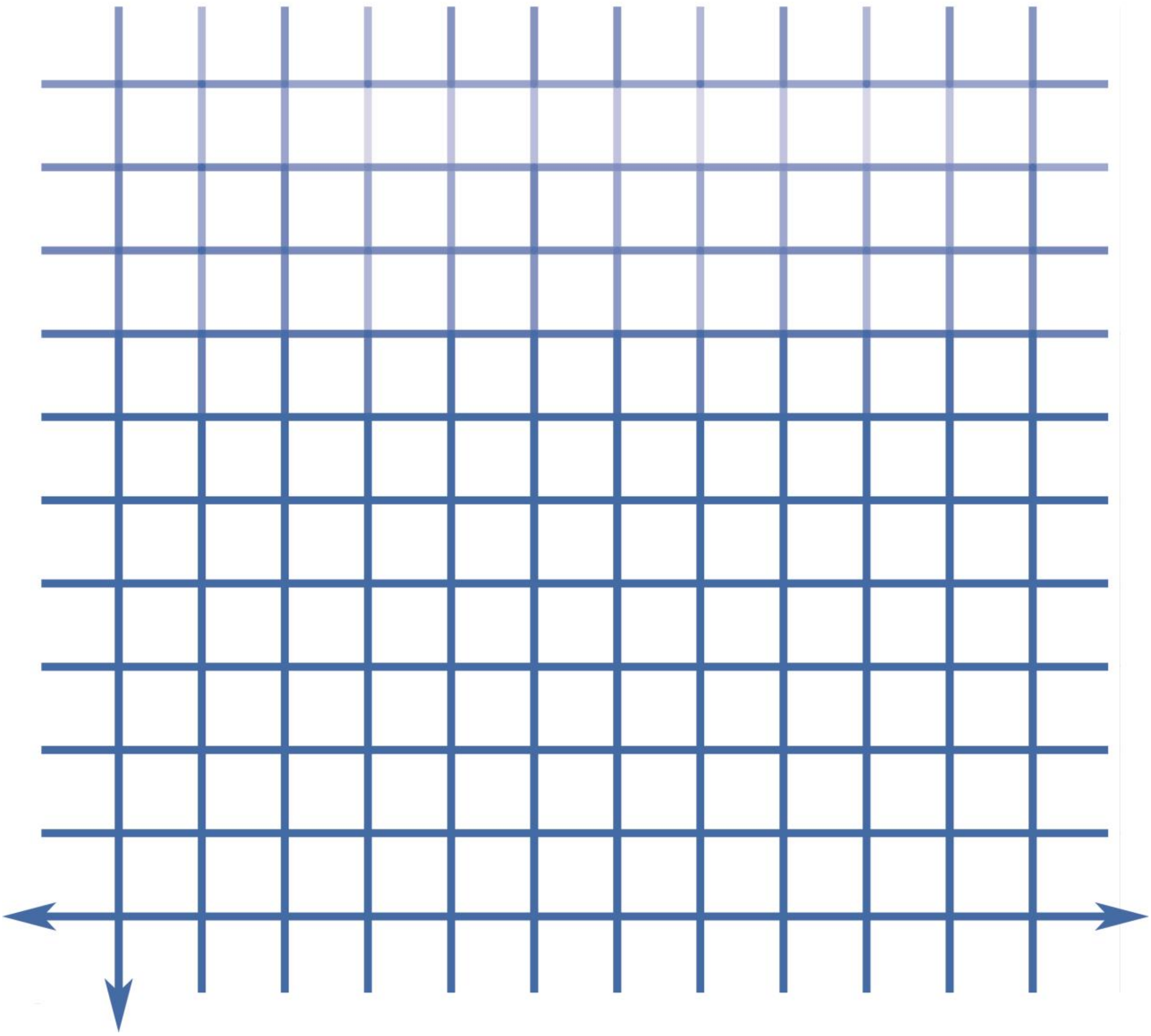
Newton's Second Law

Carolina Distance Learning
Investigation Manual



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Overview

This investigation explores Newton's Second Law of Motion and the relationship between force and acceleration. In the activity, the mass of a plastic cart is increased by adding weights in the form of washers. This cart is attached by a string to a hanging mass suspended over a pulley. As mass is transferred from the cart to the suspended weight, the cart is accelerated at an increasing rate. Students use graphical analysis to study the relationship between force and acceleration described by Newton's Second Law.

Objectives

- Define force according to Newton's Second Law of Motion
- Learn the relationship between force, mass, and acceleration through graphical analysis
- Learn how to measure force, calculate weight, and become familiar with the SI unit of force, the Newton (*N*)

Time Requirements

Preparation...15 minutes
Activity 1 ....45 minutes

Background

Classical mechanics is the branch of physics concerned with analyzing forces, their effect on matter, and the motion of objects. The distinction "classical" means that these laws apply to systems where the effects of relativity are negligible or have little measurable effect. This is the case for most of the physical events we witness, because relativistic effects apply to objects moving near the speed of light. Most mechanical systems we study on Earth can be analyzed and described in terms of classical mechanics.

Classical mechanics is sometimes referred to as Newtonian mechanics, because much of the science builds on the work of Isaac Newton, the English physicist and mathematician who lived from 1642 until 1726. When people hear the name Newton, they are likely to think of **Newton's Laws of Motion**, which they may be familiar with in one form or another. These three laws describe the relationship between force, object mass, and motion. Newton's Laws of Motion are some of the most fundamental principles of physics and are crucial to the development of modern technology. Everything from the motion of planets to the operation of sophisticated engines and machines is governed by these three simple laws.

Newton's First Law of Motion relates to the concept of **inertia**, an object's resistance to a change in motion. The first law states that an object's motion remains unchanged unless the object is acted upon by an unbalanced force (i.e., **net force**).

A book resting on a table is being acted on by opposing and equal forces. Gravity pulls down on the book, while the table pushes up on the book with an equal amount of force. The book will remain motionless until the forces are unbalanced. Consider a rocket fired into space. In space, without friction from air resistance, once the thrust from the rocket engine stops, the rocket itself will continue to travel at a constant speed in a straight line unless the rocket is acted upon by another force. This could happen if he rocket struck another object, such as an asteroid, or if the rocket entered the gravity field of a planet causing the rocket's path to curve.

Newton's Second Law of Motion states that the force acting on an object is related to the change in the objects **momentum** (***p***), which is the product of the object's **mass** (*m*) multiplied by its **velocity** (*v*).

$$\boldsymbol{p} = m\boldsymbol{v}$$

Because the mass of the object remains the same, the net force changes the object's velocity. A change in velocity is defined as acceleration, and Newton's Second Law is often described mathematically as:

$$\boldsymbol{F} = m\boldsymbol{a}$$

Where ***F*** is the net force acting on an object, *m* is the mass of the object, and ***a*** is the acceleration of the object due to the net force.

Force is measured in units of Newtons (N), where 1 Newton is equal to 1 kilogram multiplied by 1 m/s^2.

So:

$$[\boldsymbol{F}] = N$$

$$1N = 1kg \cdot 1\, {}^{m}/_{s^2}$$

In physics texts, vector quantities are usually indicated by printing an arrow over the variable representing the quantity, or as in this document, placing the letter in bold. In the equation:

$$\mathbf{F} = m\boldsymbol{a}$$

The symbols for force and acceleration are in bold, because these quantities are vectors, while mass, represented by the letter m, is a scalar quantity.

When a variable is written without bold print or between absolute value bars, only the magnitude of a variable is indicated:

$$\boldsymbol{a} = 9.8\, {}^{\mathrm{m}}/_{\mathrm{s}^2}$$

The symbol $\boldsymbol{a}$ represents an acceleration of 9.8 m/s^2 in the positive direction:

$$|\boldsymbol{a}| = 9.8\, {}^{\mathrm{m}}/_{\mathrm{s}^2}$$

The symbol $\boldsymbol{a}$ inside absolute value bars indicates an acceleration of 9.8 m/s^2 but does not specify a direction.

To indicate the units of a quantity, the variable representing the quantity is placed in brackets:

$$[\boldsymbol{F}] = N$$

Indicates that the quantity Force is measured in units of Newtons.

Consider **Figure 1**. A force of 20 *N* is acting on an object with mass of 4 kg. The acceleration of the object is 5 m/s^2. In **Figure 2**, there is a 20 *N* force applied in the forward direction and a 4 *N* force applied in the backward direction. Therefore, the net force acting on the 4 kg object is 16 *N*. The acceleration is 4 m/s^2. It should be noted that in this activity friction is ignored, but in reality frictional forces are always present, and frictional forces should be considered in order to calculate the net force.

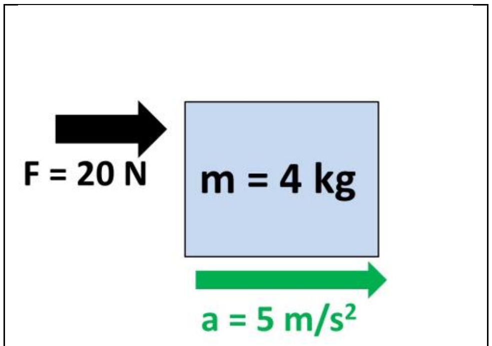

Figure 1

$$20\ N = 4\ \text{kg} \times\ 5\ {}^{\text{m}}/_{\text{s}^2}$$

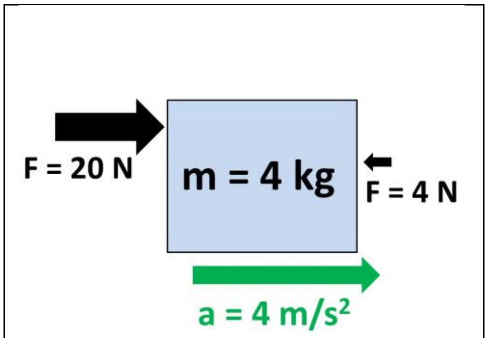

Figure 2

$$\mathbf{F}_{\text{NET}} = 20\ N - 4\ N = 16\ N$$

So, if we substitute the net force of 16 *N* acting on the object, and the known mass of the object, 4 kg, into the basic equation of Newton's Second Law, **F** = $\boldsymbol{ma}$, we can determine the object's acceleration:

$$16\ N = 4\ \text{kg}\ \times\ 4\ {}^{\text{m}}/_{\text{s}^2}$$

On Earth, the acceleration due to gravity is 9.8 m/s^2. The weight (***W***) of an object is calculated by multiplying the mass of the object by the acceleration due to gravity, represented by the symbol $\boldsymbol{g}$:

$$\boldsymbol{g} = 9.8\,{}^{\text{m}}/_{\text{s}^2}$$

The weight of a 10 kg object would be 98 *N*:

$$\boldsymbol{W} = m\boldsymbol{g} = (10\text{ kg})\left(9.8\ ^{\text{m}}/_{\text{s}^2}\right) = 98\ N$$

Newton's Third Law of Motion: states that forces occur in pairs. For every action force there is an equal and opposite reaction force. The forces are equal in magnitude and opposite in direction.

If a person jumps off a boat that is floating in the water, as the person moves in one direction the boat moves in the opposite direction, and the person does not move as far from their starting position as they would have if they had jumped from a stationary pier.

Newton's Laws of Motion can help analyze mechanical systems. The force acting on an object or part of a system can be calculated by applying Newton's Laws. These equations can also be used to calculate the acceleration that an object will experience due to an applied force.

Newton's Second Law of Motion states that the net force acting on an object is equal to the mass of the object multiplied by the object's acceleration.

This can be expressed mathematically as:

$$\boldsymbol{F} = m\boldsymbol{a}$$

Where ***F*** is the net force applied to an object, m is the mass of the object, and $\boldsymbol{a}$ is the acceleration of the object.

Note: The expression, "net force" means the vector sum of all the forces acting on an object. If the net force on an object is zero, there will be no acceleration. The object would either remain still or move at a constant speed in a straight line. A change in the velocity of an object in any direction and/or speed is the result of a net or unbalanced force being applied to that object.

In this activity, you will construct a system consisting of a hanging mass attached to a wheeled cart and graphically analyze the relationship between the mass of the system and the force acting to accelerate the system.

Materials

Included in the Mechanics Module kit	
Dynamics Cart	1
Table Clamp Pulley	1

Needed from the core equipment set:	
Tape Measure	1
String	1
Pocket Scale	1
Washers/Weights	30
Paper clip	

Needed, but not supplied:	
Books	1
Calculator or Computer	1
Masking Tape	1
Permanent Marker	1

Optional	
Smartphone/Tablet, or other digital recording device	1

Reorder Information: Replacement supplies for the DL Mechanics Module: Newton's Second Law investigation can be ordered from Carolina Biological Supply Company, kit 580404.
Call 1-800-334-5551 to order.

Safety

Safety goggles should be worn during this lab.

Read all the instructions for this laboratory activity before beginning. Follow the instructions closely and observe established laboratory safety practices, including the use of appropriate personal protective equipment described in the Safety and Procedure section.

Safety goggles should be worn during this lab. The activities in this lab involve carts containing unsecured metal masses that move and accelerate. Take care while performing these lab activities to avoid injuring hands and fingers or feet and toes with moving or falling masses. Make sure lab area is clear of pets, children, and breakable objects.

Do not eat, drink, or chew gum while performing this activity. Wash your hands with soap and water before and after performing the activity. Clean up the work area with soap and water after completing the investigation. Keep pets and children away from lab materials and equipment.

Alternate Methods for Collecting Data using Digital Devices.

Much of the uncertainty in these experiments arises from human error in measuring the times of events. Some of the time intervals are very short, which increases the effect of human error due to reaction time.

Observing the experiment from a good vantage point that removes parallax errors and recording measurements for multiple trials helps to minimize error, but using a digital device as an alternate method of data collection may further minimize error.

Many digital devices, smart phones, tablets, etc. have cameras and software that allow the user to pause or slow down the video.

If you film the experiment against a scale, such as a tape measure, you can use your video playback program to record position and time data for the carts. This can provide more accurate data and may eliminate the need for multiple trials.

If the time on your device's playback program is not sufficiently accurate, some additional apps may be available for download.

Another option is to upload the video to your computer. Different video playback programs may come with your operating system or software suite or may be available for download.

Some apps for mobile devices and computer programs available for download are listed below, with notes about their features.

Hudl Technique: http://get.hudl.com/products/technique/

- *iPhone/iPad and Android*
- *FREE*
- *Measures times to the hundredth-second with slow motion features*

QuickTime http://www.apple.com/quicktime/download/

- Free
- Install on computer
- 30 frames per second
- Has auto scrubbing capability

Preparation

1. Gather items listed in the Materials section.
2. Find a table at least 60 cm high.
3. Clear a space on the table top approximately 1–2 meters in length and at least 10 centimeters wide. The area should be level and smooth.
4. The clamp pulley should attach to the end of the table with enough space for a suspended mass to fall unobstructed to the floor. See Figure 3 for an example of the clamp pulley secured to a table top. You may place a piece of cardboard between the clamp and the table to prevent damaging the table surface.

Activity 1: Newton's Second Law

1. Place two books close together on the table near the clamp pulley, one on either side of the string. Place them close enough to the clamp to prevent the cart from running into the pulley. Make sure the books do not interfere with the movement of the string.
2. Remove the rubber stopper and circular spring from the cart if attached. Use caution when removing the spring, as it can decompress quickly and become a projectile.
3. Tie a string to the cart through the hole where the rubber stopper was attached.
4. Place the cart on the table so the front edge rests against the stopping books.
5. Thread the string over the pulley and down to the floor.
6. Unbend a paperclip to make a hook where you can suspend the washers. See **Figure 3**.
7. Cut the string near the floor and tie the free end of the string to the paperclip. When the front edge of the cart rests against the books and the string is threaded over the pulley, the paperclip and the washers will be suspended just above the floor.

Figure 3

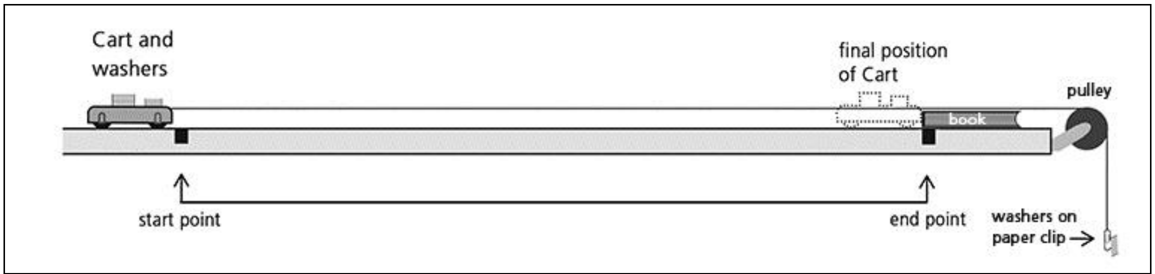

Figure 4

8. Roll the cart backward on the table away from the books and pulley, until the paperclip is just below, but not touching, the pulley. Place a piece of tape in front of the front edge of the cart (see the tan start point indicated in **Figure 4**). Label this tape as the start point or d = 0.

9. Place a second piece of tape on the table, across the path of the cart and even with stopping books. Label this tape as the end point.

10. Measure the distance from the start point to the end point. Record this value in Data Table 1.

11. Add **six** large washers and **five** small washers to the cart, and add **four** small washers to the paperclip on the end of the string.

12. Using the pocket scale, measure the combined mass of the cart with all the washers, the string, and the paper clip. This is the mass of the entire system, and this mass will remain constant during the experiment. Record the mass in Data Table 1.

13. Place the cart behind the piece of tape marking the start point, and suspend the paperclip with the initial four small washers over the pulley. **See Figure 4**

14. Release the system and allow the suspended mass to fall. If the system does not move, transfer one of the smaller washers from the cart to the paper clip hook.

15. Once you have successfully set up the system with the initial conditions that will allow the suspended mass to accelerate the cart, use the pocket scale and measure the mass of the paperclip with the small washers. Record this value in Data Table 1.

16. Set up the cart, string, and suspended mass system again, so that the mass on the paperclip is suspended from the pulley and the cart is immediately behind the start point as in **Figure 4**. The string should be taught so there is no slack.

17. Release the cart and simultaneously start the stopwatch. Stop the stopwatch when the cart contacts the stopping books.

18. Record the time in **Data Table 1**.

19. Repeat Steps 16 through 18 two more times for a total of three trials using the same number of washers to accelerate the system. Record the times for the three in Data Table 1.

20. Move one of the small washers from the cart to the paperclip.

21. Repeat the procedure in steps 19–21, collecting data for three trials with the mass of an additional washer accelerating the system.

22. Repeat the procedure using an increasing number of washers (up to seven washers) to accelerate the system.

23. Calculate the force (N) accelerating the cart by multiplying the mass of the suspended washers and the paperclip by the acceleration due to gravity ***g***= 9.8 m/s^2).

Note: Mass is the amount of matter in an object. Weight is the force of gravity on an object, which is provided in Newtons, *N*:

$$weight = force\ due\ to\ gravity = m\boldsymbol{g}$$

$$\boldsymbol{W} = \boldsymbol{F}_G = m\boldsymbol{g}$$

24. Calculate the average time of the three trials for each iteration of the experiment.

25. Calculate the square of each average time.

26. Calculate the acceleration of the system by using the **Kinematics Equation**:

$$\boldsymbol{s} = \frac{1}{2}\boldsymbol{a}\,t^2$$

Where ***s*** is displacement (the distance that the cart moved from the start point to the end point), *t*^{2} is the square of the time for the cart to move from the start point to the end point (in this experiment three times are averaged to minimize error) and ***a*** is the acceleration of the system.

Rearranging the preceding equation for acceleration gives:

$$\boldsymbol{a} = \frac{2\boldsymbol{s}}{t^2}$$

As the mass that is suspended over the pulley increases, the weight, or the force, accelerating the system increases, and therefore the acceleration of the system increases.

27. Construct a graph of force (*N*) vs. acceleration (m/s^2). The force accelerating the system in each trial is the weight of the suspended mass. The slope of the line should be the mass of the entire system.

According to Newton's Second Law of Motion, the relationship between force and acceleration is given by:

$$\boldsymbol{F} = m\boldsymbol{a}$$

In this experiment, the mass of the system, the cart, the string, the paperclip, and all the washers remained constant. The force accelerating the system was the weight of the washers. As the weight of the washers increased, so did the acceleration in a linear relationship described by the preceding equation.

28. Calculate the percent difference between the mass of the system determined experimentally using the slope of the line and the mass you recorded using the pocket scale. Remember to convert all masses to kilograms (kg).

$$percent\ difference = \left|\frac{first\ value - second\ value}{\left(\frac{first\ value + second\ value}{2}\right)}\right| \times 100\%$$

Data Table 1

Suspended Mass (kg)	Weight of Suspended Mass (mass × 9.8 m/s^2), Newtons	Time (sec)	Average Time	Average Time ^{2}	d (m)	2d (m)	Acceleration = $2d/t^2$
3 Washers		Trial 1					
		Trial 2					
		Trial 3					
4 Washers		Trial 1					
		Trial 2					
		Trial 3					
5 Washers		Trial 1					
		Trial 2					
		Trial 3					
6 Washers		Trial 1					
		Trial 2					
		Trial 3					
7 Washers		Trial 1					
		Trial 2					
		Trial 3					
Mass of the System (kg)				Slope of the Line (kg)			

Title: ____________________

Label (y-axis): ____________________

Label (x-axis): ____________________