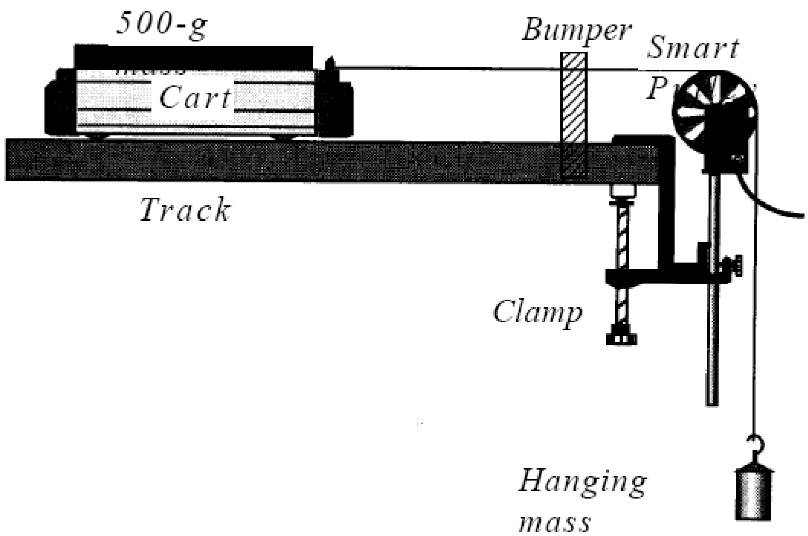
UNIVERSITY PHYSICS

EXPERIMENT 5

www.ccccd.edu/physics

COLLIN COUNTY COMMUNITY COLLEGE

Newton's 2nd Law of Motion



Produced by the Physics Staff at Collin County Community College

Purpose

In Experiments 2 and 4 you examined *how* objects move, i.e., the relationships between displacement, velocity, acceleration, and time. In this experiment you will investigate *why* objects move the way they do, i.e., what must be done to them to cause their state of motion to change.

Equipment

- 1 Pasco Track
- 1 Plunger Cart
- 1 Large Ringstand
- 1 Motion Sensor
- 1 Mass Set w/ Hanger
- 2 Leveling Feet
- 1 End Stop
- 1 Rod Clamp
- 1 Force Sensor
- 1 Roll of string

Introduction

In his laws of motion, Isaac Newton distilled the educated world's whole understanding of motion into three simple, logical statements. His first statement was that in the absence of any net external force, an object's inertia (which we measure as its mass) causes its motion (its velocity) to remain unchanged. The natural implication of this is that when a force *is* applied, the motion changes. This is, in fact, what happens, although the object's inertia still resists the *change* in motion.

Newton's second statement (arguably the most famous relationship between properties in all of science) was simply the relationship between the applied force and the change in motion. It states that when an external force is exerted on an object, its motion changes at a rate – and in a direction – that is proportional to the force.

Famous though it may be, Newton's second law immediately raises two questions in the minds of most people: First, what, exactly, is a *force*? And second, what does *proportional* really mean? Let's consider each question.

We normally think of a force as a push or a pull exerted by one object on another. Some forces require the two objects to be touching each other, such as you pushing on a broom or you pulling on a leash which, in turn, is pulling on a dog. Other forces don't require any contact – they act at a distance. Gravity and magnetism are two examples of such non-contact forces.

In physics, we define a force as anything that causes a *change in the velocity* of an object. Forces are vector quantities. We measure their magnitude by measuring the rate of change in the object's velocity, i.e., its acceleration, and we determine their direction by noting the direction of the resulting acceleration (which is not necessarily the direction of the *velocity* but is the direction of the *change in velocity*).

Proportionality is a concept you should clearly understand to succeed in physics. It is quite simply this: two variables are proportional whenever their ratio is constant. For example, x is proportional to y when, ***and only when***, x/y = constant. If x/y is constant, then obviously y/x is also constant. The value of the constant has a name; we call it the ***constant of proportionality***.

A proportional relationship can therefore be written mathematically in several forms. If the variables x and y are proportional, then:

$$\frac{y}{x} = C \quad \text{or} \quad y = Cx + D \quad \text{or} \quad x = \frac{y}{C} + F = Ey + F$$

where $C, D, E,$ and F are constants. These equations should be familiar to you as the standard forms of a linear equation. When two variable properties are proportional, we say that they are linearly related.

With those questions out of the way, let's now look at Newton's 2nd law itself. The key to understanding this fundamental relationship,

$$F = ma$$

is to keep in mind what acceleration means and which quantities are proportional. An object of mass m responds to an applied force F not in the *amount of change* in its velocity (Δv) but in the *rate of change* in its velocity ($\Delta v/\Delta t$), which we call its acceleration a. The constant of proportionality is, of course, the body's mass.

In general, you can think of this relationship in three ways:

<u>First way:</u> The product of m and a is always equal to the applied force F. If the applied force is constant, then even though the mass and acceleration may both vary, their product ma must stay constant. The two quantities are inversely proportional; i.e., if they vary, they vary in opposite directions.

<u>Second way:</u> The ratio F/m is always equal to the acceleration a. If the acceleration is constant, then even though the force and mass may both vary, their ratio F/m must stay constant. The two quantities are directly proportional, if they vary, they vary in the same direction.

<u>Third way:</u> The ratio F/a is always equal to the mass m. If the mass is constant, then even though the force and acceleration may both vary, their ratio F/a must stay constant. The two quantities are directly proportional, if they vary, they vary in the same direction.

How you use Newton's 2nd law to describe any system in motion or to solve any problem involving objects in motion depends on which of the three quantities, F, m, or a, is constant.

In this experiment you will investigate Newton's 2nd law of motion in various ways to:

1. Verify the relationship he predicted between the force applied to an object, the object's mass, and its resulting acceleration.
2. Validate Galileo's theory that objects of all masses when moving freely through the air have the same constant downward acceleration, regardless of the direction of their motion.

Theory

Net Force Applied to a Mass

Newton's laws of motion apply to anything that moves. Specifically, his second law predicts what will happen to the motion of an object when an external force is applied to it.

We begin this examination of motion with the simple ideal condition of zero friction, which allows you to control the net force acting on the object. We usually approach this ideal condition in the real world by considering very low-friction situations such as a hockey puck sliding over ice or over an air table. In this experiment, the moving object will be a low-friction wheeled cart on a one-dimensional track. While not zero, the frictional force on the cart is very much smaller than the applied force, so we can safely ignore it.

A. Variable Force Applied to a Constant Mass

When a force *F* is exerted on an object of mass *m*, whether or not it is already in motion, the object will accelerate in the direction of *F* with a magnitude of $a = F/m$. This is true even if the object is really a system of two or more objects connected so that they move together.

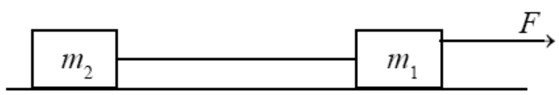


Figure 5.1. Force applied to masses

Consider two objects of masses m_1 and m_2, connected by a taut string on a frictionless table. Assume the objects can move together in a straight line without friction. If you pull on object m_1 with a force *F* in the direction away from m_2, the string will remain taut as it relays the force to m_2, and both bodies will accelerate to the right as in Figure 5.1. The value of their acceleration is:

$a = F/(m_1 + m_2)$

You can avoid pulling directly on m_1 if you place the string over a frictionless pulley so that m_1 hangs down from it. The force *F* will then be supplied by gravity, as shown in Figure 5.2.

The force of gravity pulling m_1 downward is called its *weight* (F_W), and it is equal to its mass m_1 multiplied by the constant acceleration due to gravity *g*, i.e., $F_W = m_1 g$. Because of the string, this force is also applied to m_2.

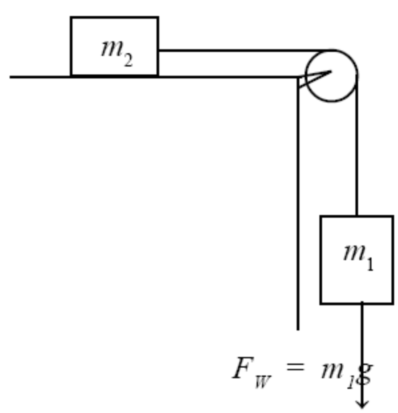


Figure 5.2. Weight applied to mass

So you can now write Newton's equation as

$a = m_1 g/(m_1 + m_2)$

You can increase the force applied to the masses by increasing the mass m_1. If you do this by simply moving some mass from m_2 to m_1, the total mass being accelerated will remain constant while the applied force is being increased, so the acceleration should increase proportionally to m_1.

You will do this in Part A of the experiment. You will measure the acceleration of a two-object system for various values of the applied force, and compare it to the acceleration predicted by Newton's equation. The object m_2 will be the cart carrying various masses, and m_1 will be a mass hanger holding various masses.

The velocity of the total system will be equal to the velocity of the string, which is proportional to the rotary speed of the pulley wheel. By measuring how the rotary speed of the pulley changes with time, you can determine how the velocity of the two-mass system changes with time; i.e., its acceleration.

B. Variable Force Supplied by Gravity

If a single object such as a frictionless cart moves freely on a ramp inclined at an angle θ, it will be accelerated toward the bottom of the ramp. This is the same as a freely-falling object except the acceleration is less. It's the same situation whether the cart is moving up or down the ramp. An acceleration down the ramp when the cart is moving up the ramp means, of course, that its speed is decreasing.

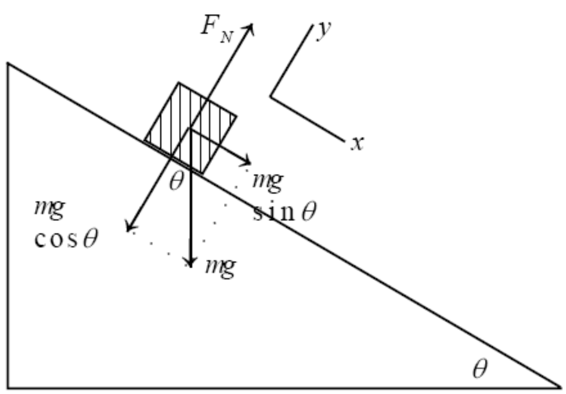


Figure 5.3. Forces on block on a ramp

You can find the value of the cart's acceleration down the ramp, *a,* by considering the forces acting on it as it moves. In Figure 5.3, the force of gravity (the cart's weight *mg*) acts vertically downward. The component of the cart's weight parallel to the ramp is *mg* sin θ, and the component perpendicular to the ramp is *mg* cos θ. The ramp pushes up on the cart with a normal force F_N that is equal and opposite to *mg* cos θ, so the net force on the cart in that direction is zero. The cart therefore has no acceleration perpendicular to the ramp.

The cart's acceleration parallel to the ramp, *a*, is the ratio of the parallel force $mg \sin \theta$ to the mass *m*, or

$a = g \sin \theta$

This acceleration will be directed down the ramp, no matter which direction the cart is moving. Because the cart's velocity is proportional to the time ($v = v_o + at$), a graph of velocity vs. time will be linear. The slope of the graph will be positive for motion down the ramp (*v* and *a* have the same sign) and will be negative for motion up the ramp (*v* and *a* have opposite signs), and the value of the slope will be equal to the cart's acceleration. Because the cart's acceleration is constant, a graph of *a* vs. *t* will be linear and horizontal, and the value of *a* will be the position of the horizontal line on the ordinate scale. The motion of the cart (its change in position with time) can be measured directly with a motion sensor.

C. Variable Force Supplied by You

Rather than applying a force to the cart through a string running over a pulley as in Part A, or by gravity as in Part B, you can apply the force directly with your hand. Using sensors to directly measure both the force and the resulting acceleration of a constant-mass cart, you can verify that the force and the acceleration are still proportional even when they are not constant.

Procedure

You will use both the Smart Pulley and the Motion Sensor to measure the cart's acceleration when a net force is applied to it three different ways. In Part A, the force is applied by a string tied to the cart. In Part B, the applied force is a component of the cart's weight. In Part C, you apply the force with your hand and measure it with the Force Sensor. With the power switched off, connect the following sensors to the Interface:

1. Plug the Smart Pulley cable to Digital Channel 1.
2. Plug the Motion Sensor cables to Digital Channels 2 and 3.
3. Plug the Force Sensor cable to Analog Channel A.

A. Variable Force Applied to a Constant Mass

For this part you will use the Smart Pulley sensor to measure the velocity of the cart as it is pulled by a string attached to a weight suspended over the pulley. Data Studio plots the changing velocity of the cart. You will analyze the graph of velocity vs. time to determine the acceleration of the cart.

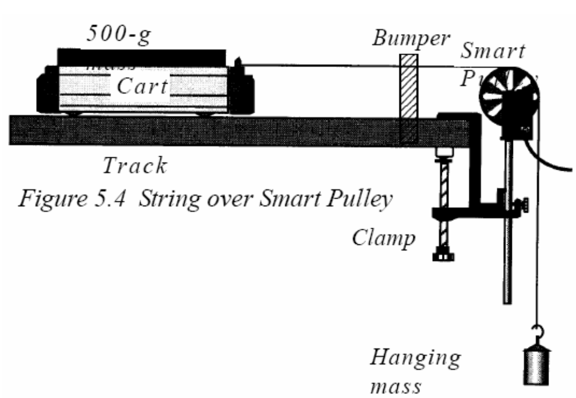


Figure 5.4 String over Smart Pulley

1. Fasten the leveling feet about 50 cm in from each end of the track, and place the track with one end projecting over the end of the table. Place the cart on the track and adjust the leveling feet so that the cart doesn't roll on its own one way or the other.
2. Mount the bumper a few inches in from the end of the track that hangs off the table, then attach the Smart Pulley to that same end of the track using the Universal Table Clamp as shown in the figure above.
3. Weigh the empty cart and record its mass above Table 5.1.
4. Cut a 1 m length of string and tie a small loop at each end. Hook one loop over the plunger lock of the cart and hook a mass hanger in the other loop. Thread the string over the pulley, ensuring that it doesn't rub anywhere.
5. Pull the cart to the left until the mass hanger is just below the clamp and place something on the track to hold the cart in place (or a group member can just hold the cart with their hand). Adjust the pulley height so that each end of the section of string between the cart and the pulley is about the same height above the track.
6. Plug the Smart Pulley cable to Digital Channel 1. Switch on the computer, monitor, and interface. Open Data Studio and select *Create Experiment.*
7. In the Experiment Setup window, drag the Smart Pulley icon to Digital Channel 1.
8. Open a Graph display and select *velocity*. This will display a graph of velocity vs. time.
9. Place a total mass of 500 g on the cart, such that the total mass M of the cart is now the mass of the empty cart + 0.5 kg. Record this total mass M in Table 5.1.
10. Place 50 g of mass on the hanger so the total hanging mass m is the mass of the empty hanger + 0.05 kg. The force applied to the cart is the weight of the total hanging mass, $F_W = mg$. Record the value of m and the value of F_W in Table 5.1.
11. With the cart free to roll down the track, pull the cart back up the track until the hanging mass is at the smart pulley. Press *Start* and release the cart (try to stop the cart right before it hits the bumper). Press *Stop* when the cart stops.
12. Highlight the linear portion of the graph, and click the *Scale to Fit* button to resize the graph to fit the data. Click the *Fit* button and select *Linear Fit* from the menu. The equation of the line that best fits the data contains the y-intercept $\boldsymbol{b}$ and the slope $\boldsymbol{m}$.
13. The slope of the Velocity vs. Time graph is the cart's acceleration. Record it in Table 5.1 (with appropriate units).
14. Increase the applied force by transferring 50 g from the cart to the hanger. Record the new values for M, m, and F_W in Table 5.1.
15. Repeat steps 11–14 four times, transferring 50 g from the cart to the hanger for each trial until 0.30 kg remains on the cart.
16. Use Newton's Second Law and your measured values of M, m, and F_W to *calculate* the acceleration in each trial. Record your calculated acceleration values in Table 5.1.
17. Now repeat steps 11–15 five more times, but keep the hanging mass constant at m = 0.2 kg and increase the total cart mass from M = mass of empty cart + 0.30 kg to M = mass of cart + 0.50 kg in four equal steps. Record the new values for M, m, and F_W in Table 5.2.
18. Use Newton's Second Law and your measured values of M, m, and F_W to *calculate* the acceleration in each trial. Record your calculated acceleration values in Table 5.2.
19. Calculate and record the percent difference between the calculated and measured accelerations in each trial.
20. Remove the cart, masses, string, and hanger. Remove the Smart Pulley and clamp. Remove the leveling feet from one end of the track. Set all this equipment aside.

B. Variable Force Supplied by Gravity

In this part you will use the motion sensor to follow the position of the cart after you give it a push up the inclined track. Data Studio will calculate the velocity and acceleration of the cart as it moves up and back down. You will analyze graphs of position vs. time, velocity vs. time, and acceleration vs. time.

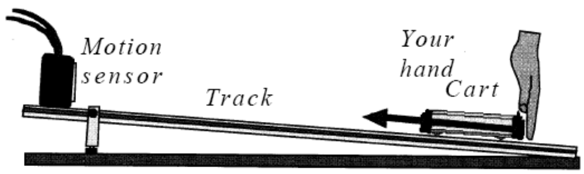
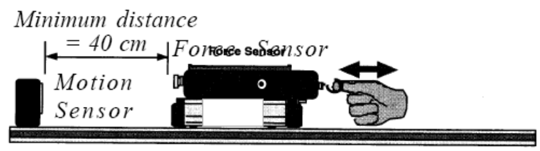


Figure 5.5. Motion sensor tracking cart

1. Unscrew the remaining leveling feet at the other end of the track to raise that end as high as possible. Place the Motion Sensor at the high end as shown in Figure 5.5.
2. Plug the Motion Sensor cables to Digital Channels 1 and 2, create a new experiment in Data Studio, and drag the Motion Sensor Icon to channels 1 and 2 (in Data Studio).
3. In Data Studio create the graphs Position (m) versus Time (s), Velocity (m/s) versus Time (s), and Acceleration (m/s^2) versus Time (s).
4. Use a protractor to set the angle of the track to about θ = 5° and record this measured angle θ and sin θ in Table 5.3.
5. Make a trial run to make sure the motion sensor is properly aligned to see the cart as it moves. Place the *empty* cart on the low end of the track, press Start, and give the cart a firm push up the track. Don't push the cart so hard that it goes any closer than 40 cm to the sensor.
6. Click Stop when the cart returns to the bottom of the track. Click the *Scale to Fit* button. If the velocity graph does not resemble a straight line, realign the sensor and try again. When you get a good plot, delete your trial data runs.
7. To begin your actual data run, press Start and give the cart another firm push. Collect data until the cart returns to the bottom of the track, then click Stop. If the data points do not appear on the graph, check the alignment of the motion sensor and try again.
8. Click the *Scale to Fit* button to rescale all three graphs to fit the data.
9. Highlight the linear portion of the velocity graph, click the *Fit* button, then select *Linear Fit*. The slope of the best-fit straight line (coefficient ***m*** in the equation) is the cart's average downward acceleration. Record this value in Table 5.3.
10. In the acceleration graph, drag a rectangle to select the horizontal portion of the graph. This portion shows the cart's downward acceleration before it stopped at the bottom of the track.
11. Click the *Statistics* menu button in the acceleration graph, then select *Mean* from the menu. The mean value of acceleration in your selected region is shown. Record this value in Table 5.3.
12. Use the ringstand and pivot clamp to raise the track to a 10° inclination angle and repeat steps 7 – 11. Repeat these steps again with the track raised to inclination angles of 15° and 20°.

13. Plot a graph of acceleration vs. sin θ using acceleration values from each method (*slope* of velocity graph and *mean* of acceleration graph). Use these two graphs to calculate the acceleration of gravity *g*. Using an accepted value of $g = 9.81$ m/s^2, calculate the percent error of *g* for each method.
14. Remove the pivot clamp, ringstand, and bumper, and screw in the leveling feet on the left end so the track is once again level with the Motion Sensor at its left end.

C. Variable Force Supplied by You



In this part you will use your hand to push and pull the cart back and forth on a level track. The force sensor will measure the force your hand exerts on the cart while the motion sensor measures the motion of the cart. Science Workshop will calculate the cart's acceleration as it moves. You will analyze a graph of force vs. acceleration to determine the mass of the cart.

1. Use tape to mount the Force Sensor to the empty cart so the hook end of the sensor is above the plunger and points away from the Motion Sensor, as in the figure above.
2. Add 0.2 kg of extra mass to the cart. Tape it in place, if necessary. Record the total mass of the cart + force sensor in Table 5.4.
3. Plug the Force Sensor cable to Analog Channel A, and create a new Experiment. Drag the Force sensor and Motion sensor to the Interface in Data Studio. Open a graph display and select Force. Drag the Acceleration icon from the Data listing to the graph's horizontal axis. The graph should now plot Force (N) vs. Acceleration (m/s^2).
4. Make a trial run to make sure the motion sensor is properly aligned to see the cart as it moves. Place the cart on the track and press the Tare button on the Force sensor. Click Start, firmly grasp the Force sensor's hook, and push and pull the sensor to make the cart move back and forth about once per second. Make sure the cart doesn't come too close to the Motion sensor. When you have collected data for about 5 seconds, click Stop.
5. Click the *Scale to Fit* button to rescale the graph to fit the data. If the Motion sensor does not provide smooth acceleration data for the graph (i.e., if the data is very chaotic), realign the sensor and try again. When you get a good plot, delete your previous trial runs.
6. Press the Tare button on the Force sensor, then begin your actual data run. Push and pull the cart for five seconds as in step 4. Run #1 will appear in the Data list.
7. Click the *Scale to Fit* button. Drag a rectangle with the mouse to select the entire graph. Click the *Fit* button and select *Linear Fit.* The slope of the best fit straight line (coefficient ***m***) is the total mass of the cart + sensor. Record this mass in Table 5.4.
8. Repeat steps 6 and 7 for two more trials, adding an additional 0.2 kg to the cart for each trial.
9. Calculate and record the three percent differences between the masses obtained from the graphs and the measured masses.
10. Quit the Data Studio program, shut down the computer, disassemble all the equipment, neatly coil all cables and secure them with twisty-ties, and return all equipment to the setup cart.