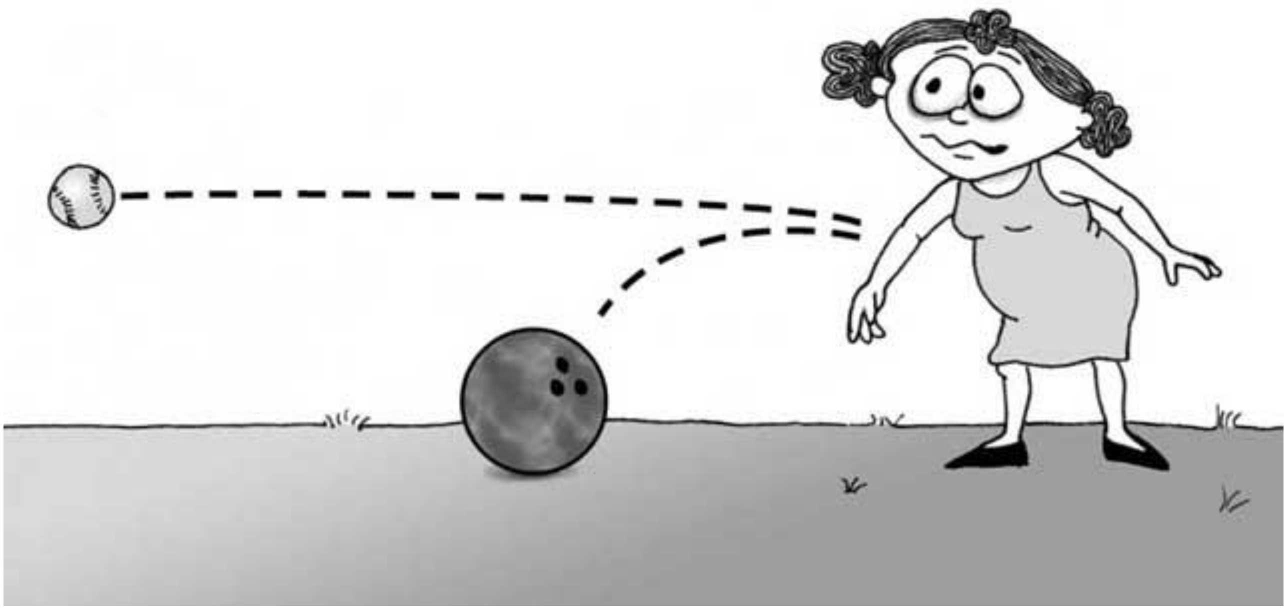
Forces

Experiment Central: Understanding Scientific Principles Through Projects, 2010

A force causes or changes an object's motion: It is a push or pull on an object. Forces have both a size and a direction. Forces also work in pairs: In order for a force to occur there must be an interaction between two objects. For example, when throwing a boomerang a person applies a force to the object that makes it move. Weightlifting exerts a force on the weight to pull it upward. These are forces that occur by physical contact between the two objects.

Yet forces also occur upon a person who is standing still. Forces are, in fact, occurring on everyone and everything on Earth, along with celestial objects. In these forces, two interacting objects exert a push or pull with no physical contact between them. An example of this force is gravity. Gravity is the force of attraction between any two objects in the universe.

Guiding principles
While there have been numerous contributors to people's knowledge of forces, English scientist Isaac Newton (1642-1727) formulated the laws of motion, the rules that explain how forces work. As he was working on the laws of motion, Newton also explained the effect of gravity throughout the universe. In 1687 Newton published his landmark work *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy),*which gave people a new understanding of the universe and laid the foundation for the development of physics.
Newton developed three laws of motion to explain forces:



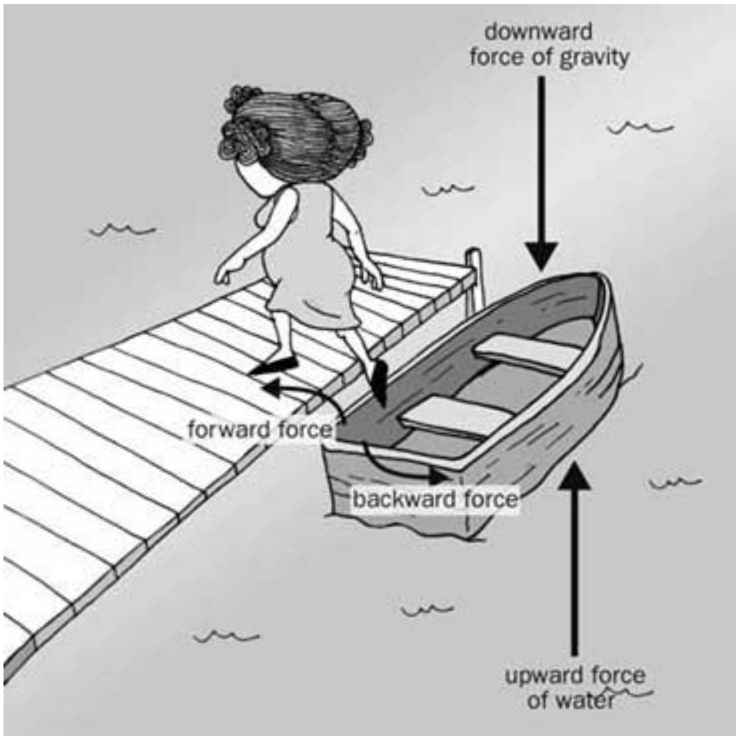
First law of motion: With no force, an object at rest will stay at rest, and an object moving in a certain direction and speed will remain moving in that same path and velocity. Velocity is the speed of an object in a particular direction. This resistance of an object to change its motion is called inertia. The greater the mass of an object is, the more force is needed for the object to overcome its inertia. For example, a toy train moving around a track would require relatively little force to make it move compared with the push a real train would need.

Second law of motion: When a force acts upon an object it will accelerate. Acceleration is the rate of change in velocity. The acceleration of an object depends upon the size of the force and the mass of the object. The relationship between these variables in mathematical terms is: Force (F) = Mass of Object (m) x Acceleration of Object (a), or $F = ma$, which can also be written $a = F/m$. As the force increases, the acceleration will also increase. The more mass an object has, the lower the rate of acceleration.

An example of this law is evident when comparing the force needed to throw two objects, such as two balls. If Ball 1 has 10 times the mass as Ball 2 and a pitcher throws the balls with equal force, then Ball 1 will accelerate at one-tenth the acceleration of the lighter ball. To make the two balls accelerate at the same rate, the pitcher will need to use ten times more force on Ball 1 than on Ball 2.

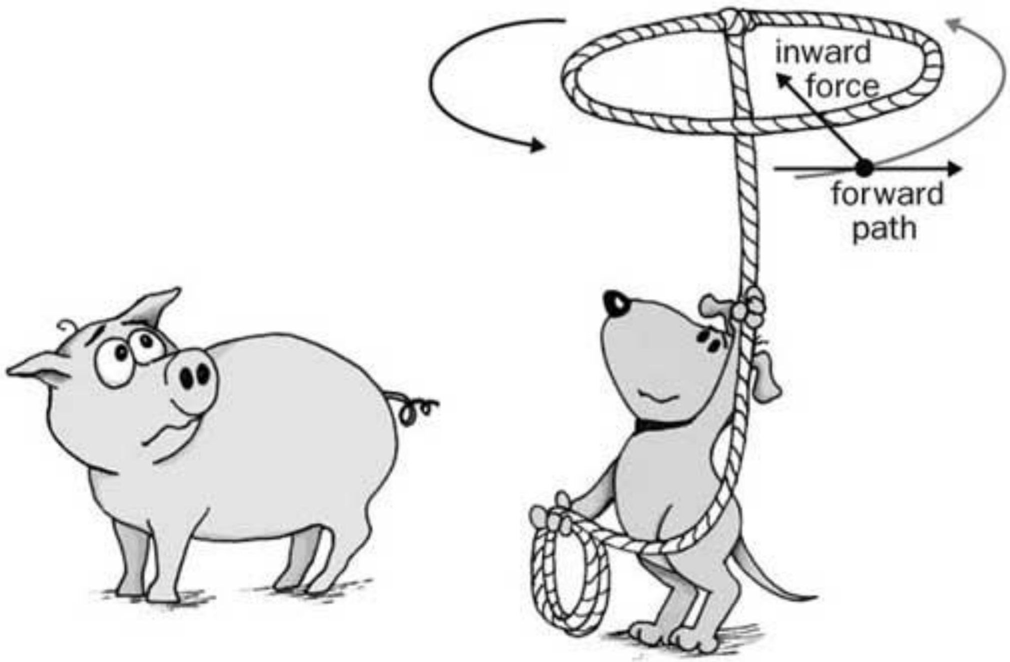
Third law of motion: For every action, there is an equal and opposite reaction. This law states that forces always work in pairs. When one force moving in a certain direction acts upon another force, then there must be a force of equal strength moving in the opposite direction.

There is usually more than one force at work. For example, when a boat is sitting still at the dock the force of gravity pulls with a downward force and the water responds with an equal and opposite upward force. A person who boards the boat and pushes it away from the dock exerts another force. The push starts the boat moving gradually away from the dock due to its inertia. Yet once moving, the boat will need that same amount of force to stop it. When the boat stops and the boater steps back onto the dock, that is another force. As the person steps off the boat with a push, the boat will move back in the opposite direction.



Round and round we go

Newton's laws explain both straight motion and circular motion. A force that causes an object to follow a circular path is called centripetal force. The word centripetal comes from the Latin words *centrum* and *petere,* meaning center seeking. (This force is often confused with centrifugal force, meaning center fleeing. Centrifugal force is not considered a true force, as there is no force acting upon the object; it is only the tendency of the object to continue in a straight line. See Ocean chapter.) Anytime there is a circular movement around a central point, then centripetal force is at work.



Centripetal force is based on Newton's first law of motion that states an object will travel along a straight path with constant speed unless a force acts upon it. Thus, for a circular motion to occur, there must be a constant force pulling the object towards the center of the circle. This force is always directed inward. For a planet orbiting the Sun, the force is gravity; for a ball twirling on a string, the force is the tension in the string; for a loop in a roller coaster ride, the force is applied by the curved track.

An object moving in a circle is constantly accelerating because it is continuously changing its direction. This is true even if the object is moving at a uniform speed. (Acceleration is a change in velocity and velocity is the speed of an object in a particular direction.) The amount of centripetal force needed to keep an object moving in a circular path depends upon its acceleration, along with its mass.

When the centripetal force is taken away, the object follows Newton's first and third laws: Its inertia causes the object to move in a straight line and the force by which it moves outward is equal in strength and opposite in direction.

Words to Know

Acceleration

The rate at which the velocity and/or direction of an object is changing with respect to time.

Centripetal force

A force that pushes an object inward, which causes the object to move in a circular path.

Control experiment

A setup that is identical to the experiment, but is not affected by the variable that acts on the experimental group.

First law of motion (Newton's)

An object at rest or moving in a certain direction and speed will remain at rest or moving in the same motion and speed unless acted upon by a force.

Force
: A physical interaction (pushing or pulling) tending to change the state of motion (velocity) of an object.

Gravity
: Force of attraction between objects, the strength of which depends on the mass of each object and the distance between them.

Hypothesis
: An idea in the form of a statement that can be tested by observation and/or experiment.

Inertia
: The tendency of an object to continue in its state of motion.

Second law of motion (Newton's)
: The force exerted on an object is proportional to the mass of the object times the acceleration produced by the force.

Third law of motion (Newton's)
: For every action there is an equal and opposite reaction.

Variable
: Something that can affect the results of an experiment.

Velocity
: The rate at which the position of an object changes with time, including both the speed and the direction.

EXPERIMENT 1

Newton's Laws in Action: How do water bottle rockets demonstrate Newton's laws of motion?

Purpose/Hypothesis

The laws of motion explain how force affects the movement of an object. Many objects such as trains, airplanes, and theme park rides demonstrate these laws. In this experiment, you will work with a water bottle rocket to observe Newton's laws. After constructing a basic launcher you will use a plastic two-liter bottle and water to measure the force required to lift the rocket. By adding water to the rocket, you will increase its mass.

A rocket exhibits all three of Newton's laws of motion. Newton's first law states that an object at rest will stay at rest, and an object in motion continues in motion. When the rocket is sitting on the launcher it is an object at rest. Once a force is applied to the rocket and it is in motion, it continues in motion. Newton's second law explains that when a force acts upon an object it causes the object to accelerate. This is seen when force--in this case, the pressure of the air pumped in the bottle by the tire pump--is exerted on the rocket. The rocket launches and accelerates in upward motion. Newton's third law refers to reactions, stating that for every action there is an equal and opposite reaction. When the rocket lifts, the air and water that filled the bottle are forced out of the spout in the opposite direction while propelling the rocket higher.

The rocket will be your object, either at rest or in motion. The force is the pressure of the air pumped inside the launcher. As the rocket propels forward, the water will escape and cause the mass to change.

Before you begin, make an educated guess about the outcome of this experiment based on your knowledge of rockets and Newton's laws of motion. This educated guess, or prediction, is your hypothesis. A hypothesis should explain these things:

- the topic of the experiment
- the variable you will change
- the variable you will measure
- what you expect to happen

A hypothesis should be brief, specific, and measurable. It must be something you can test through further investigation. Your experiment will prove or disprove whether your hypothesis is correct. Here is one possible hypothesis for this experiment: "The greater the amount of water in the rocket (bottle), the more air pressure (force) is required for launching."

In this case, the variable you will change is the mass (the amount of water in the rocket). The variable you will measure is the force (the air pressure in the rocket) required for liftoff.

What Are the Variables?

Variables are anything that might affect the results of an experiment. Here are the main variables in this experiment:

- the amount of water in the bottle
- the air pressure in the bottle
- the tightness of the seal between bottle and launcher
- thickness of the bottle
- preciseness of gauge on tire pump

In other words, the variables in this experiment are everything that might affect the mass of the rocket and the force applied by the compressed air inside. If you change more than one variable, you will not be able to tell which variable impacted the rocket liftoff.

Level of Difficulty

Difficult.

Materials Needed

To build launcher:

- 5 feet (1.5 meters) of ¾-inch CPVC pipe (available in the plumbing section of home improvement or hardware stores). It is generally a yellowish color and is sold in 10-foot (3-meter) lengths. Use a saw or PVC cutters to cut.
- 7 inches (18 centimeters) of ½-inch CPVC pipe
- T-joint fitting with ¾-inch ends and a ½-inch center for CPVC pipe
- 45-degree elbow with ¾-inch ends for CPVC pipe
- 90-degree elbow with ¾-inch ends for CPVC pipe
- two end caps for ¾-inch CPVC pipe
- PVC primer (minimal amount)
- PVC glue/cement (minimal amount)
- roll of masking tape (½- or ¾-inch wide)

- 2 inches (5 centimeters) of ⅝-inch inner diameter clear vinyl tubing (available at hardware or home improvement store)
- tire valve stem (ask at a local tire store and explain it's for a science experiment; it may be possible to get a donation)
- saw or PVC cutting tool
- drill
- paring knife
- expandable pipe wrench; it needs to have the capacity to hold the ¾-inch cap
- scrap wood block
- safety goggles
- protractor

For launch:

- water
- bike tire pump with pressure gauge. Make sure it is a full-size pump. Small pumps that fit in a backpack may not create enough force.
- measuring cup
- 2-liter plastic soda bottle
- permanent marker
- paper towels or a drying rag
- tape measure
- open space
- partner and adult present when using tools

Approximate Budget

$18 (not counting the bicycle pump).

Timetable

1 hour to build; 30 minutes to dry; 30 minutes for experiment.

How to Experiment Safely

This is an involved experiment. It should be constructed and performed with the assistance of another person. Have an adult present when working with the drill and saw or similar cutting device. Wear safety goggles during construction. It is important to work in a well-ventilated area when working with PVC cement. The rocket should be launched in a large open area. Do not attempt to catch the rocket. It is also important to only use plastic bottles and not glass bottles.

Step-by-Step Instructions

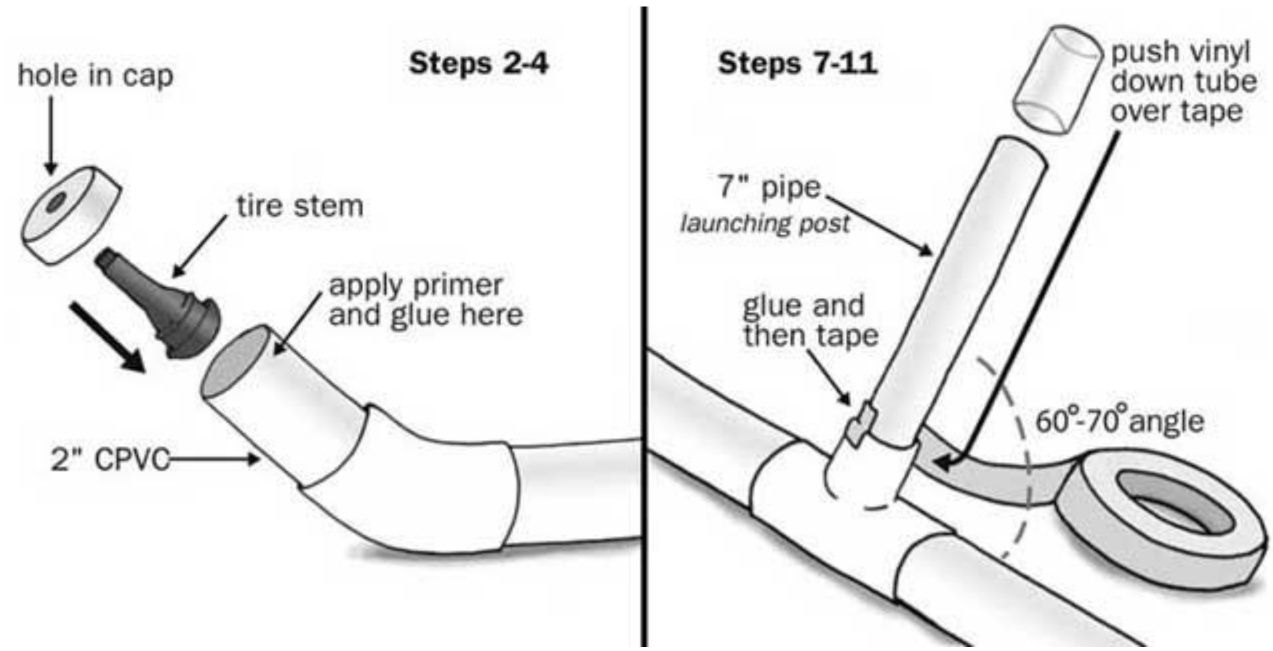
To build the launcher:

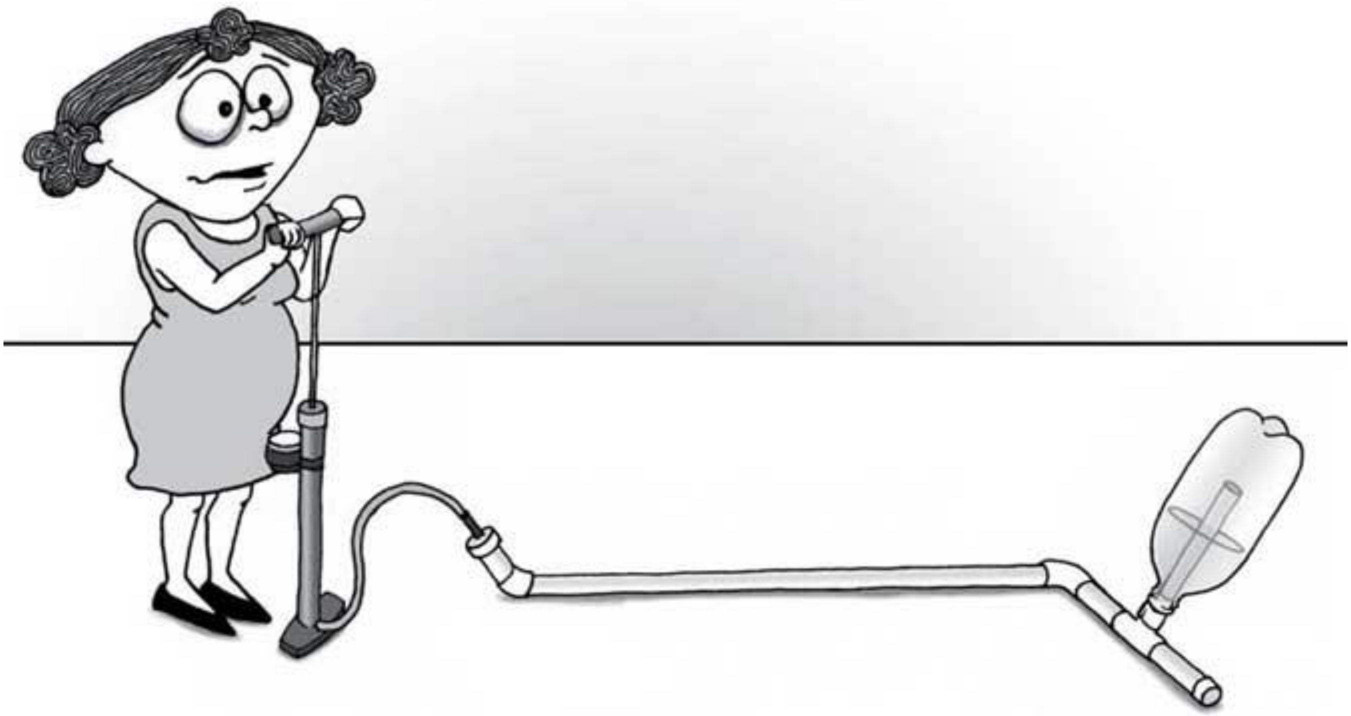
1. From the 5-foot (1.5-meter) piece of the ¾-inch pipe cut two 6-inch (15-centimeter) pieces and one 2-inch (5-centimeter) piece. The remaining piece should be approximately 46 inches (117 centimeters) long.
2. One person will clamp one of the ¾-inch end caps with the wrench. Rest the cap on the scrap wood block to avoid drilling through the workspace. Have the helper drill a hole in the center of the PVC cap. The hole needs to be large enough for the tire stem to come part way through, approximately ¼ inch. Check to ensure the tire valve is able to be pushed partway through the hole. It may be necessary to trim away part of the rubber around the valve stem. This may be done with a paring knife.
3. Glue the end cap to the 2-inch length of pipe: Push the valve stem partway through the 2-inch (5-centimeter) tube. Apply primer to the outside of the 2-inch (5-centimeter) pipe, the inside of the end cap, and a small amount to the base of the valve stem. Next, apply the glue over the primer. (Note: PVC glue dries very quickly and makes a lasting bond. Once the two pieces of CPVC touch, you have only a few seconds before they are connected forever.)
4. Hold the valve stem partway out of the 2-inch (5-centimeter) piece of pipe and place it through the hole on the end cap. The valve stem should stick out of the hole in the cap. Pull firmly and slightly twist the valve stem, making sure it is secure. Wipe away excess glue.
5. Connect the 46-inch (117-centimeter) piece of pipe to the 2-inch (5-centimeter) piece with the 45-degree elbow. Apply the primer and glue to the inside of the elbow and the outside of the long piece. Insert the pipe into the elbow. Next, apply to the other side of the elbow and the outside of the 2-inch piece. Firmly press the elbow on the 2-inch piece of pipe. Wipe away excess glue. Set aside to dry.
6. Cut a 7-inch (18-centimeter) length of the ½-inch pipe. This will become your launching post.
7. Connect the launching post to the T-joint fitting. Glue the two ¾-inch CPVC pieces to the ends of the T-joint fitting. First apply the primer, then the glue again to the inside of the connector and the outside of the pipe. The 7-inch piece of ½-inch CPVC is then glued into the empty hole of the T-joint fitting.
8. Tape masking tape around the connection of the 1/2 in PCVC post and the T. It will be necessary to make several wraps and tapering the tape slightly (about an inch or two) up the post. Next, push the 2-inch piece of clear vinyl tubing down the tube and over the tape. Use an extra piece of the ¾-inch PCVC to assist in pushing the tubing down snugly over the tape. The tape and tubing will create a stopper for the bottle to fit on.
9. Using your bottle, test to see if the tape and tubing will create a tight seal. If the seal is not tight, remove the tubing and add more tape.
10. Glue the 90-degree elbow to the long piece made in the first five steps.
11. Use your protractor to glue the T post to the 90-degree elbow. The post should create between a 70-degree and 60-degree angle with the ground, pointing away from the valve stem end of the launcher. Do not angle the post less than 45 degrees.
12. Allow launcher to sit about 30 minutes to dry.

To launch:

1. In an open area, fill the 2-liter bottle with 2 cups (about 0.5 liter) of water.

2. Place the launch post in the bottle and push for a snug fit. Mark this spot with a permanent marker. (It works best to turn the launcher slightly on its side, and gently "roll" it back to its standing position with the bottle on top. This way the water will not come out of the bottle.)
3. Attach the tire pump to the valve nozzle.
4. Pump the tire pump to fill the bottle with air. Keep pumping at a slow and steady pace until the rocket launches. The helper should note the gauge and record the pressure required for liftoff.
5. Repeat launch for two more trials, noting the force (air pressure) and distance for each trial.
6. Fill the 2-liter bottle with 3 cups (about 0.75 liter) of water.
7. Repeat Steps 2 through 5.
8. Fill the 2-liter bottle with 4 cups (about 1.0 liter) of water.
9. Repeat Steps 2 through 5.





Data for Rocket Launch (averages)

	Pressure/Force	Distance
2 cups water		
3 cups water		
4 cups water		

Summary of Results

Examine your results to determine which amount of water required the greatest amount of force for liftoff? Was your hypothesis correct? Hypothesize what would happen if you changed the bottle size, and maintained the water amount. What would occur if a cone top and wings were attached to the rocket? Write a brief summary of the experiment and your analysis.

Troubleshooter's Guide

Below is a problem that may arise during this experiment, a possible cause, and a way to remedy the problem.

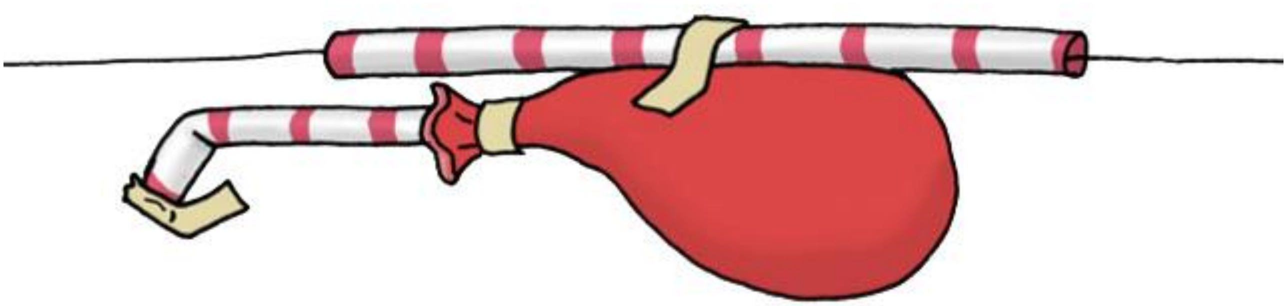
- **Problem:** The rocket will not take off.
- **Possible cause:** Make sure your seal is tight. Wipe the stopper off after each launch. Check the tire pump to determine if it is attached appropriately. The pump may be too weak to perform the launch.

Change the Variables

There are several ways you can modify the experiment by changing the variables. You can change the sizes of the bottle and maintain the water amount. Another approach could include using various bottle sizes and filling each bottle to half of capacity, rather than a uniform water amount. If you have access to a football field, you could perform the experiment on the field and attempt to measure the distance of each launch. It may be beneficial to prop the launcher on a block of wood to create more of an angle (do not go less than 45 degrees).

Modify the Experiment

You can also explore Newton's laws by conducting a simpler version of the rocket experiment. You will need a piece of wire several feet long. Gather together a balloon, tape measure, string, wide straw and masking tape. Slip the straw onto the wire so that it moves about freely, and securely tie the wire to two objects, such as two chairs.



Blow up the balloon, place a straw in it and tape the straw so that no air escapes. Bending the straw will help keep the air from escaping. Place a piece of masking tape on the end of the straw to seal the air inside. Tape the straw to the balloon. As you look at your experimental setup, think about all the forces. The air, for example, is a force acting on the outside of the balloon.

Now take the tape off the end of the straw. What happens as the air escapes? Newton's third law of motion states that for every action force there is an equal and opposite reaction force. The air is the action and the movement of the straw is the opposite reaction. Measure how far your balloon moved along the wire. How can you make the straw move a shorter distance? How can you make it move farther? Experiment with blowing up the balloon different amounts. After each trial, write down the distance the straw moved.

EXPERIMENT 2

Centripetal Action: What is the relationship between distance and force in circular motion?

Purpose/Hypothesis

Centripetal force is any force that acts on an object at a right angle to its path of motion. The constant right angle force results in the object moving in a circular path. In this experiment, you will examine how altering the force and radius will affect the acceleration of an object. Radius is the distance from the center to the outer point of a circle. The object's mass will stay the same.

A piece of string will have a mass attached to one end and washers creating the force attached to the other end. You will first alter the radius, and then alter the force. For a more accurate measure of how many times the mass completes a circle or revolution, you will count how many times it revolves in 30 seconds. That number will then be divided by 30 to give its revolutions per second. Another way to increase accuracy is to complete three trials of each experimental trial.

Comparing the results to a control experiment will help you isolate each variable and measure the changes in the dependent variable. In this experiment there will be two variables that you will change, one at a time. Only one variable will change between the control and the experimental setup each time. In the first part, the distance will change when the radius increases. In the second part, the force will change. At the end of the experiment you can compare each of the results to the standard experiment.

Before you begin, make an educated guess about the outcome of this experiment based on your knowledge of centripetal force. This educated guess, or prediction, is your hypothesis. A hypothesis should explain these things:

- the topic of the experiment
- the variable you will change
- the variable you will measure
- what you expect to happen

A hypothesis should be brief, specific, and measurable. It must be something you can test through further investigation. Your experiment will prove or disprove whether your hypothesis is correct. Here is one possible hypothesis for this experiment: "The greater the force, the greater the acceleration; the greater the radius; the lower the acceleration."

In this case, the variable you will change is the force and the distance, one at a time. The variable you will measure is the acceleration of the mass.

What Are the Variables?

Variables are anything that might affect the results of an experiment. Here are the main variables in this experiment:

- the force
- the radius
- the mass

In other words, the variables in this experiment are everything that might affect the acceleration of the mass. If you change more than one variable at the same time, you will not be able to tell which variable had the most effect on centripetal force.

Level of Difficulty

Easy to Moderate.

Materials Needed

- spool of thread with narrow hole
- ruler
- ten metal washers of equal size
- 3 feet (90 centimeters) of string
- masking tape
- watch with second hand
- bobbin, small spool of thread, rubber stopper or other lightweight object that can be easily tied
- helper

Approximate Budget

$2.

Timetable

30 minutes.

How to Experiment Safely

Be careful when swinging the mass and check to ensure the knot is tight. Make sure you are working in an open area.

Step-by-Step Instructions

1. Slide the string in the large spool of thread and move the spool up 2 feet (0.6 meters).
2. On the long side of the string, attach four metal washers (this is the force) to the end and secure with a knot.
3. Tie the bobbin or rubber stopper to the end of the short side of the string. This is the mass.
4. Wind a piece of tape about 1 inch (2.5 centimeters) below the spool to make sure it does not slide down and change the radius. Mark the string at the point above the tape.
5. Hold the washers with one hand and begin to swing the mass until it is moving parallel to the floor. Practice swinging at a steady rate.
6. While you are swinging, have your helper time 30 seconds and count the number of revolutions the bobbin makes.
7. Repeat Step 6 two more times so that you have three trials. This is your standard experiment.
8. Remove the tape and slide the spool down 1 foot (0.3 meters) towards the washers. Reattach the tape about 1 inch (2.5 centimeters) below the spool.
9. Again, time the number of revolutions in a 30-second period, then repeat for two more trials. Note the results.
10. Return the spool to its beginning position, reattaching the tape at the marked point on the string.
11. Double the number of washers to eight. Support the washers until you have a steady swing and then have your helper time 30 seconds while you count the revolutions. Repeat two more times and note the results.

Summary of Results

Determine the time for each revolution per second by dividing the total revolutions by 30. Once you have the revolutions per second for each trial, average the three trials. Make a chart of your data. Compare how long it took to complete a full circle when the radius lengthened. How much force would it take to have the revolutions of different radiuses be the same. Look at how the increased force compares with the acceleration of the lesser force? What would happen to the acceleration if you halved the force? Hypothesize how the force and/or radius would need to change if the mass was doubled and you wanted to keep the acceleration equal.

Troubleshooter's Guide

Below is a problem that may arise during this experiment, a possible cause, and a way to remedy the problem.

- **Problem:** The radius looked like it was changing.
- **Possible cause:** The paperclip might have slid loose. Use a tight paperclip and make sure it is attached firmly, then repeat the experiment.

Change the Variables

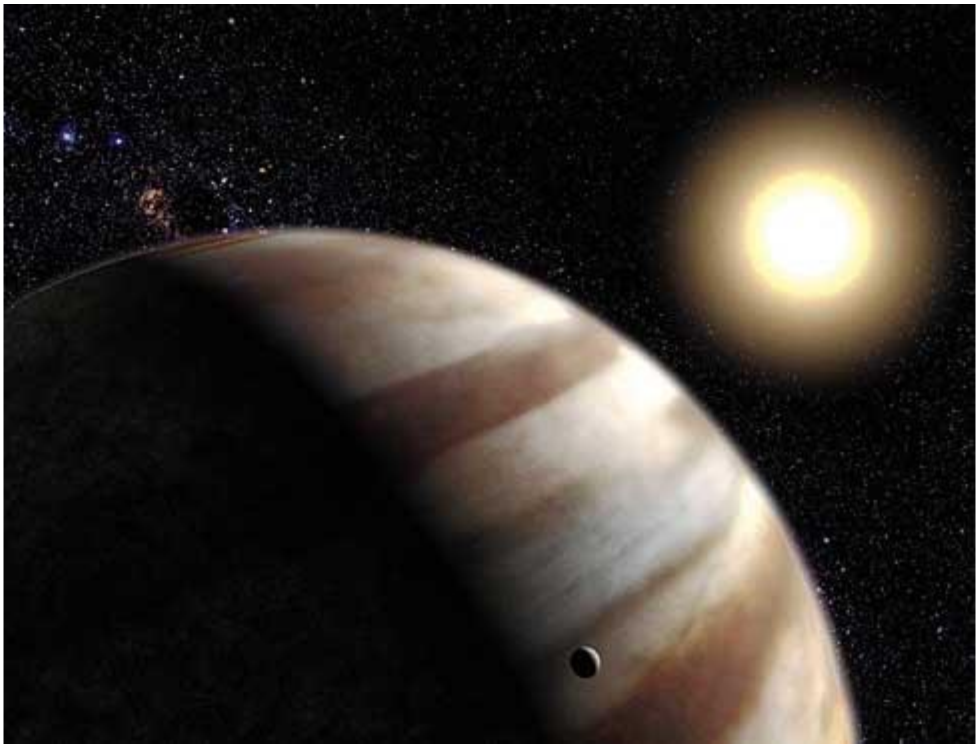
You can continue to experiment on changing the variables in this experiment in new ways and new combinations. Try to halve the force and halve the radius. Look at what occurs if the radius is tripled and the force remains constant. You can also change the mass of the object, making it lighter or heavier. Make sure you secure the mass tightly to the string and try to work in an open area.

Design Your Own Experiment

How to Select a Topic Relating to this Concept

Force is a broad topic that has many possible experiments. To gather ideas on force, you can observe how force is applied in daily life. Look at sporting events and playground rides to see the application of Newton's laws and centripetal force. You could also research how celestial bodies in the universe apply centripetal force.

Check the Further Readings section and talk with your science or physics teacher to learn more about force.



Steps in the Scientific Method

To conduct an original experiment, you need to plan carefully and think things through. Otherwise, you might not be sure what question you are answering, what you are or should be measuring, or what your findings prove or disprove.

Here are the steps in designing an experiment:

- State the purpose of--and the underlying question behind--the experiment you propose to do.
- Recognize the variables involved and select one that will help you answer the question at hand.
- State your hypothesis, an educated guess about the answer to your question.
- Decide how to change the variable you selected.
- Decide how to measure your results.

Recording Data and Summarizing the Results

Your data could include charts and graphs to display your data. If included, they should be clearly labeled and easy to read. You may also want to include photographs and drawings of your experimental setup and results, which will help other people visualize the steps in the experiment.

If you are preparing an exhibit, you may want to display your results, such as any experimental setup you designed. If you have completed a nonexperimental project, explain clearly what your research question was and illustrate your findings.

Related Projects

There are many possible projects related to force. You could construct simple machines to experiment with the amount of force required for work. These projects could explore how force varies with distance and mass. Astronomers depend on the principles of centripetal force to help them predict orbits and revolutions. You could examine how the planets, suns, and moons each have their own unique orbits due to the principles behind centripetal force. You could also explore the force of gravity with everyday objects.

Further Readings

- Christianson, Gale E. *Isaac Newton and the Scientific Revolution.* New York: Oxford University Press, 1998. The personal life story of Newton and his work.
- Clark, John O. E. *Physics Matters!* Danbury, CT: Grolier Education, 2001. Provides a clear explanation of the science of physics with pictures and applications.
- "Newton's Laws of Motion." *NASA Glenn Research Center.* http://www.grc.nasa.gov/WWW/K-12/airplane/newton.html (accessed on February 3, 2008). Explanations and illustrations of Newton's laws of motion presented with different details for different grade levels.
- "Skateboard Science." *The Exploratorium.* http://www.exploratorium.edu/skateboarding (accessed on February 3, 2008). A look at the science of skateboarding and how it relates to centripetal force.

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